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Capturing economic and social value from hydrocarbon gas flaring and venting: solutions and actions

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Abstract: This second paper on hydrocarbon gas flaring and venting builds on our first, which evaluated the economic and social cost (SCAR) of wasted natural gas. These emissions must be reduced urgently for natural gas to meet its potential as an energy-transition fuel under the Paris Agreement on Climate Change and to improve air quality and health. Wide-ranging initiatives and solutions exist already; the selection of the most suitable ones is situation-dependent. We present solutions and actions in a four-point ('Diamond') model involving: (1) measurement of chemicals emitted, (2) accountability and transparency of emissions through disclosure and reporting, (3) economic deployment of technologies for (small-scale) gas monetization, and (4) an 'all-of-government' approach to regulation and fiscal measures. Combining these actions in an integrated framework can end routine flaring and venting in many oil and gas developments. This is particularly important for low- and middle-income countries: satellite data since 2005 show that 85 per cent of total gas flared is in developing countries. Satellite data in 2017 identified location and amount of natural gas burned for 10,828 individual flares in 94 countries. Particular focus is needed to improve flare quality and capture natural gas from the 1 per cent 'super-emitter' flares responsible for 23 per cent of global natural gas flared.

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

JEL classification: Q3, Q4, Q5

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Notes: This study is complemented by an earlier WIDER Working Paper written by the same authors (Romsom and McPhail 2021): 'Capturing Economic and Social Value from Hydrocarbon Gas Flaring and Venting: Evaluation of the Issues'.

Abbreviations and units are at the end of the paper.

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1 Introduction

Natural gas is seen as an important energy source in the energy transition towards a light-carbon or zero-net-carbon future. In many comparison studies for climate and air quality, gas is a more beneficial fuel than coal and heavy fuel oil in power generation, industrial use, and transportation. However, the benefits of the use of natural gas are significantly impaired when global emissions from gas flaring and venting are considered.

Routine flaring and venting of natural gas are generally accepted practices and are pervasive in the oil and gas industry. The main purpose is to get rid of associated petroleum gas (APG), a by-product in the production of oil. The decision to flare or vent natural gas by oil and gas companies is often based on commercial criteria that exclude externalities such as air quality, health and climate impact. Moreover, flaring and venting wastes a valuable energy source that could be captured and utilized for beneficial purposes.

In our first working paper on gas flaring (Romson and McPhail 2021), we established the scale, scope, and impact of hydrocarbon flaring and venting. Linking GGFR, IEA, EPA, and other data sources, our first working paper provides an integrated assessment of natural gas flared and vented by the oil and gas industry, including the amounts and damages of chemicals released into the atmosphere.

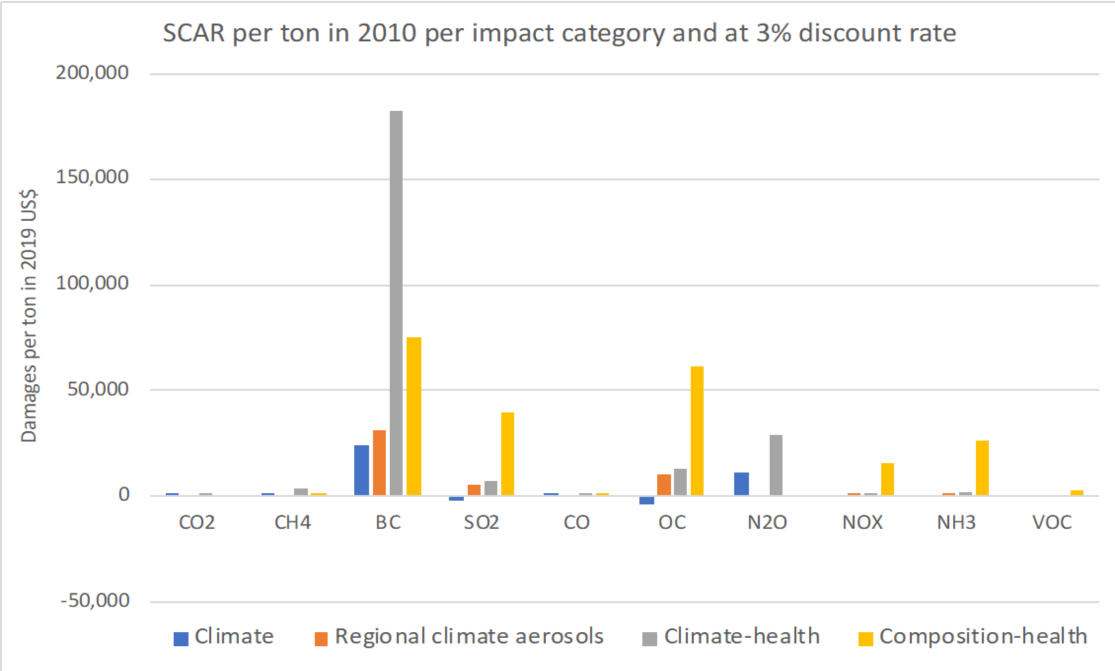
The history of gas flaring and venting has shown that large fugitive emissions and large volumes of flaring are not inevitable by-products of oil production. Between 1996 and 2010, significant progress was made to reduce gas flaring among the top 30 emitting countries, with Nigeria and Russia as notable examples. Between 1994 and 2014, overall volumes of fugitive emissions—which include gas flaring—increased. Nevertheless, there are also regions and countries which 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 have 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, reducing 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. Since 1994, the 'rest of the world' countries outside the flaring top 30 countries reduced their flaring volumes by 36 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: Russia, Iraq, the US, Iran, Venezuela.

A major result of our first working paper on gas flaring is to show these atmospheric releases and their social impact in a consistent representation. Different emissions affect climate, air quality, health, and environment differently. These wider-ranging impacts from this broader spectrum of releases are captured in a multi-impact economic valuation framework of social cost of atmospheric release (SCAR) that assigns a social cost per ton for each individual release, including:

carbon dioxide (CO_2), methane (CH_4), black carbon (BC), nitrogen and sulphur oxides (NO_X and SO_X), volatile organic compounds (VOCs), organic carbon (OC), carbon monoxide (CO), ammonia (NH_3) and nitrous oxide (N_2O); see Figure 1.

Figure 1: Impact categories' contributions to Shindell social cost of atmospheric releases

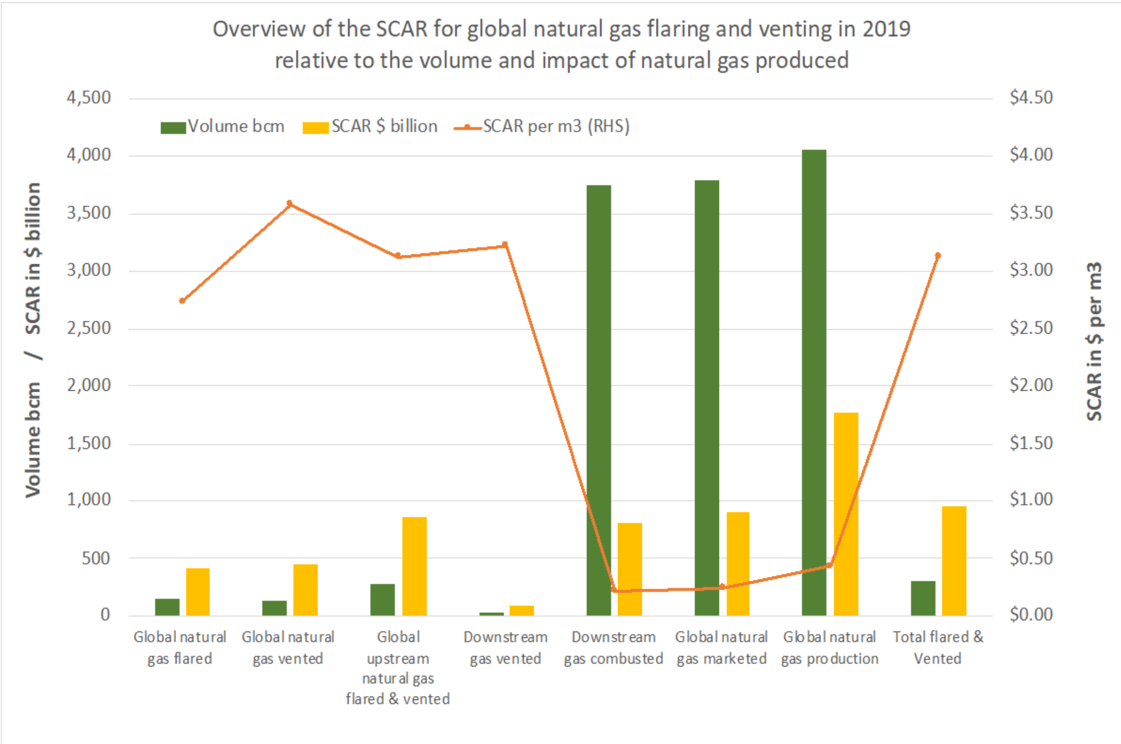


Source: authors' illustration based on 2015 data from Shindell (2015), corrected for NO_X and VOC added.

Some 6.9 per cent of globally produced natural gas is flared (3.7 per cent) or vented (3.2 per cent) in upstream oil and gas operations, contributing half of the total SCAR of natural gas. Downstream venting adds an additional 0.7 per cent, bringing the global total of gas flared and vented to 7.6 per cent. The global volume of natural gas flared and vented has not reduced since the year 2000. Because of poor flaring operations, the social cost per volume flared is 12.6 times higher than under perfect combustion. Therefore, poor flare operations negate most of the benefits that flaring has over venting (the SCAR for venting is 16 times higher than for perfect combustion); see Figure 2. 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. Various countries have shown positive results in reducing flaring and fugitive emissions, providing experience that others can build on.

The global social cost of 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. This analysis provides unambiguous support 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 from poor-quality to high-quality flaring (i.e. a system and operations that provide 98 per cent destruction efficiency) and avoiding super-emitter flares.

Figure 2: Overview of the social cost of flaring and venting relative to the volume and impact of global natural gas produced



Note: the SCAR (in $ bn) from upstream flaring and venting, representing less than 7% of the volume of produced natural gas, exceeds the SCAR from downstream gas combustion (92% of produced natural gas); emissions are based on 2017 data; costs in 2019 US$.

Source: reproduced from Romsom and McPhail (2021), Figure 18.

Furthermore, the application of gas capture technologies for unprocessed natural gas can create significant revenue opportunities. If 75 per cent of all natural gas flared and vented globally were to be captured, it would provide an additional natural gas sale value of US$40 bn per year (assuming an average gas price of $4/MMBtu). These commercial opportunities 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 aerosol-induced hydrologic cycle changes provide benefits in health and for other economic activities, such as agriculture, that are expected to significantly increase the added value from these emission reductions. If all the natural gas flared and vented globally were to be captured and brought to market, it could supply more than all of South and Central America's gas consumption, plus all of Africa's power needs.

This second working paper further addresses the integrated framework (which we refer to as the '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 socioeconomic cost analysis, detailed in our previous paper, into the Diamond model provides the means to construct an abatement strategy that captures both the economic and the social value from hydrocarbon gas flaring and venting.

2 Overcoming impediments to reducing natural gas flaring and venting

In our previous working paper, summarized in the previous section, we presented 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 flare and vent. However, it is worth re-emphasizing that prudent operators can reasonably be expected to 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 also important. 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 necessary gas infrastructure is to implement oil and gas regulation that makes it mandatory to have a development solution for APG. However, this is not a common practice. Norway is one of the few countries which have policies and regulations that disallow the practice of routine flaring to produce oil. A second impediment to stopping 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 are conducted inadequately. Apart from capacity, this is also a capability issue.

The measurement of fugitive emissions, including flaring and venting, is difficult in the absence of (accurate) metering. Flared and vented APG streams are generally not measured. Hence, data are sparse and estimates often unreliable. Remote sensing technologies are increasingly capable of 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, could and 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 working paper 1 demonstrated (Romsom and McPhail 2021).

The 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 a picture of the true scale of the opportunity costs and the potential value for the country. There is therefore less incentive to facilitate the infrastructure developments necessary to capture the natural gas that is 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[1] should be avoided and penalties imposed for not meeting flare quality standards. Measurement of air quality should also be part of a mandatory

[1] A super-emitter gas flare creates a very large SCAR due to its high flow rate (i.e. more than 5 MMscfd) and/or its poor flaring quality (i.e. a destruction efficiency of 80% or lower, releasing ten times or more the amount of chemicals other than CO_2 compared with a well-operated flare under similar flow rates). Based only on flow rate considerations, a small fraction (6.6%) of all global flares are super-emitters, consuming 61% of natural gas flared (see also Figure 18).

measurement scheme. As gas flaring is easier to detect and monitor, there is a risk that oil producers dispose of their gas though vents instead of gas flares to avoid detection. Improved methane detection levels and high spatial resolution from satellite sensors are important tools to ensure the improved measurement of methane emissions and the 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 commercial development of APG it is often necessary to aggregate the produced gas from multiple producers to achieve 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 require ownership of the gas produced to be centralized in the state can 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 may want to price the cost of externalities, such as emissions of gases, particulates, produced water, energy inefficiency, etc., in to the fiscal framework for oil and gas taxation. Whereas development of APG may not meet commercial thresholds, such fiscal measures improve the commercial break-even for gas monetization projects and incentivize producers to utilize resources that would otherwise be wasted. Other incentives to reduce flaring and venting could include common infrastructure to aggregate the gas, improving access to markets (transportation and local market development), benchmarking and best practice sharing, technology development and implementation (e.g. sponsored piloting of technologies), etc. Governments may also reduce barriers to provide tax credits for the importation of certain technologies and equipment that could make APG developments commercial, when such equipment cannot be locally fabricated.

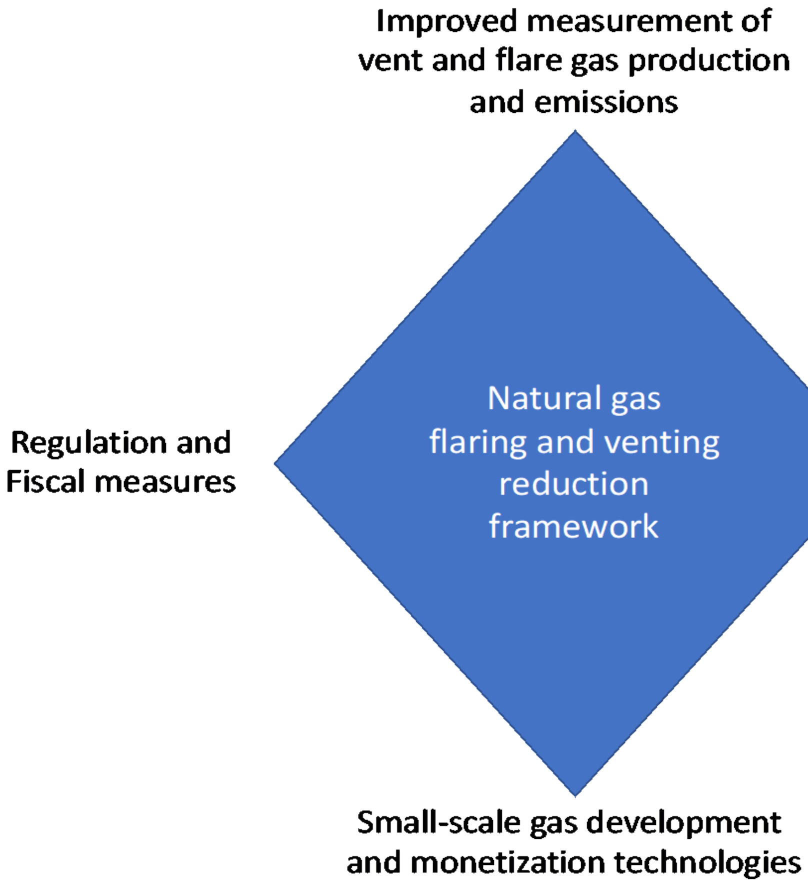
Finally, governments could stimulate local gas market development, or in the case of gas-to-wire, stimulate electricity market development by providing gas price guarantees or electricity feed-in tariffs over a limited period of time to promote infrastructure development while reducing investment risk. Such measures would be best co-ordinated with the government's strategy on renewables expansion, particularly since natural gas supports renewables in power generation (Romsom and McPhail 2020b).

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

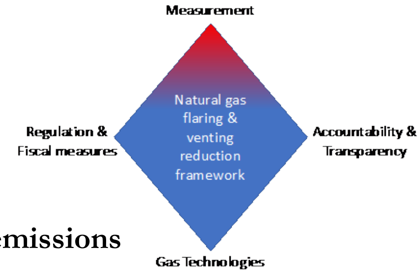
In conclusion, there are wide-ranging initiatives and solutions to overcome the current impediments to the utilization of APG. The selection of which initiatives are most suited is situation-dependent. However, the continuous improvement of gas monetization technologies, in combination with improved measurements, accountability, transparency, and reporting and with regulations and fiscal measures, provides the potential for an integrated framework to end routine flaring and venting in many oil and gas developments (see Figure 3). 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.

The paper now turns to a more detailed discussion of these categories of possible initiatives as summarized in the 'Diamond model' diagram in Figure 3.

Figure 3: Integrated 'Diamond model' framework to end routine flaring and venting



Source: authors' illustration.



3 Improved measurement of vent and flare gas production and emissions

We consider the following component issues in this section of the paper: metering of flared and vented gas; remote sensing of satellites to assess flaring and venting; Nigeria's Gas Flare Tracker; and systemic under-reporting of emissions.

Measurement of vent and flare gas: key points

- Natural gas that is being flared and vented is seldom metered. Reliable and continuous metering and data logging should be required for every vent and flare exceeding a minimum size, to assess volumes emitted and to establish opportunity costs and social costs from these practices. Metered flare and vent data can also provide the basis for fiscal measures.
- Under-reporting of flaring and venting appears to be a systemic issue in the oil and gas industry. Third-party verification for atmospheric emissions is absent. Without reliable data, the development of flaring and venting reduction solutions is being hampered.
- In the absence of physical meters, satellite data are being used to establish volume estimates for individual flares. Such technology is now also becoming practicable for methane emissions. In some countries, such as Nigeria, VIIRS Nightfire (VNF) satellite data are being used as the basis for determining the taxation of individual oil and gas companies for the gas that they flare.
- When different satellite data are combined, this provides higher accuracy on volumes flared. In particular, poorly operated flares with a high degree of smoking are likely to be underestimated by VNF.
- Even more importantly, satellites that measure other emissions (such as NO_2, SO_2, methane, etc.), when combined with VNF, can provide key information on flaring quality. SCAR damages from flaring increase dramatically when flares are poorly operated.
- Flare quality is seldom measured, and regulatory frameworks are inadequate or not enforced. Consequently, operational standards and the compliance of oil and gas operators in their flaring and venting practices are often poor.
- Further work is needed to develop models that calibrate satellite observations with metered data and other local emissions data, to enable satellite-based SCAR assessments for individual flares.
- Combining emission data from individual flares and vents with transport models and other geographical information (such as population density) allows the assessment of regional distributions of SCAR from local emitters.
- The combination of satellite data for flaring and venting and geographical information also provides the opportunity to rank flares and vents on their potential for commercialization. Natural gas rates and distance to market are the two key criteria for gas capture and monetization.
- It is critical that satellite data of atmospheric emissions are made available in the public domain (as is the case for VNF) and therefore accessible to third parties for verification and to the public for transparency. There is a risk that commercial satellites may limit data sharing by imposing charges, or by granting proprietary access to data on flare and vent areas to emitting companies only.

The lack of reliable data from venting and flaring has been an obstacle to understanding the true scale and impact of these emissions. There are multiple reasons why data are lacking.

3.1 Metering of flared and vented gas

Natural gas that is being flared and vented is seldom metered. Observational studies from gas flaring highlight the need for continuous and high-density read-outs of flare emissions. Unprocessed gas streams can be highly irregular in terms of flow rates and composition. Conrad and Johnson (2017) highlight flow irregularity as a particular concern. In one flaring example, 10 per cent of the instantaneous flare data was responsible for 56 per cent of the measured black carbon (BC) emissions. This flow irregularity requires metering technology that can handle the dynamic range in terms of rates and composition. Individual point measurements may not be reliable, and continuous metering and data logging are required. Moreover, regular physical sampling of the flare stream for compositional analysis can assist flare (re-)design and good operations. In addition, using local optic measurements to determine the degree of smoking of flares is a proven method of assessing flare quality and BC emissions.

3.2 Remote sensing by satellites to assess natural gas flaring

In addition to physical metering on flaring and venting sites, technology advancements now also provide the opportunity to measure emissions from space using specialized satellite sensors. This has a number of advantages:

- there is no need to make investments in local meters;
- there is no requirement for site access to assess flaring and venting operations: data aggregation and processing can be done remotely and does not require local resources;
- satellite data provide an independent and objective assessment;
- a high degree of spatial resolution enables atmospheric emissions to be attributed to individual emission sources, but also to be easily aggregated;
- satellite data are generally in the public domain and therefore accessible by third parties for verification, promoting transparency;
- multiple satellite overpasses enable daily measurements, during both day and night-time;
- satellite sensors can distinguish the release of different chemicals and thereby enable SCAR assessments that are based on chemical compositions;
- combining information from different satellite sensors can improve spatial and emission volume accuracy;
- satellites can assess not only the point of emission but also the subsequent distribution of atmospheric releases, enabling SCAR assessments that are geography dependent.

Since the launch of the Suomi National Polar-Orbiting Partnership (S-NPP) satellite on 21 November 2011, its Visible Infrared Imaging Ratiometer Suite (VIIRS) is regularly used by multiple organizations for the remote assessment of natural gas flaring (see Table 1 and Figure 4). The VIIRS source data are made publicly available by the US National Oceanic and Atmospheric Administration (NOAA).[2] With 22 imaging and radiometric bands covering wavelengths from 0.41 to 12.5 microns, VIIRS has a wide range of applications,[3] including the detection of radiant heat from fires such as flares. During night-time overpasses, the VIIRS is able to make use of both visible light and infrared detectors to identify night fires (VNF), significantly improving detection of smaller hotspots. Gas flares are identified as small, high-intensity, and high-temperature heat sources of fixed location and can be distinguished from other fires and hotspots (Elvidge 2015). The current VNF detection limit is 0.26 m^2 for 1,800 K heat sources such as flares. New algorithms using multiple spectral bands can further enhance this flare detection threshold (Elvidge et al. 2019). The integration of VIIRS data with other satellite sensor data and oil and gas field and facility databases can further eliminate potential false positives. VIIRS has been successfully deployed in a large number of studies and applications.

[2] NOAA, 'Visible Infrared Imaging Radiometer Suite (VIIRS)', Washington, DC: US Department of Commerce.

[3] VIIRS provides sensor data records for more than 20 environmental data categories including clouds, sea surface temperature, ocean colour, polar wind, vegetation fraction, aerosol, fire, snow and ice, vegetation, and other applications.

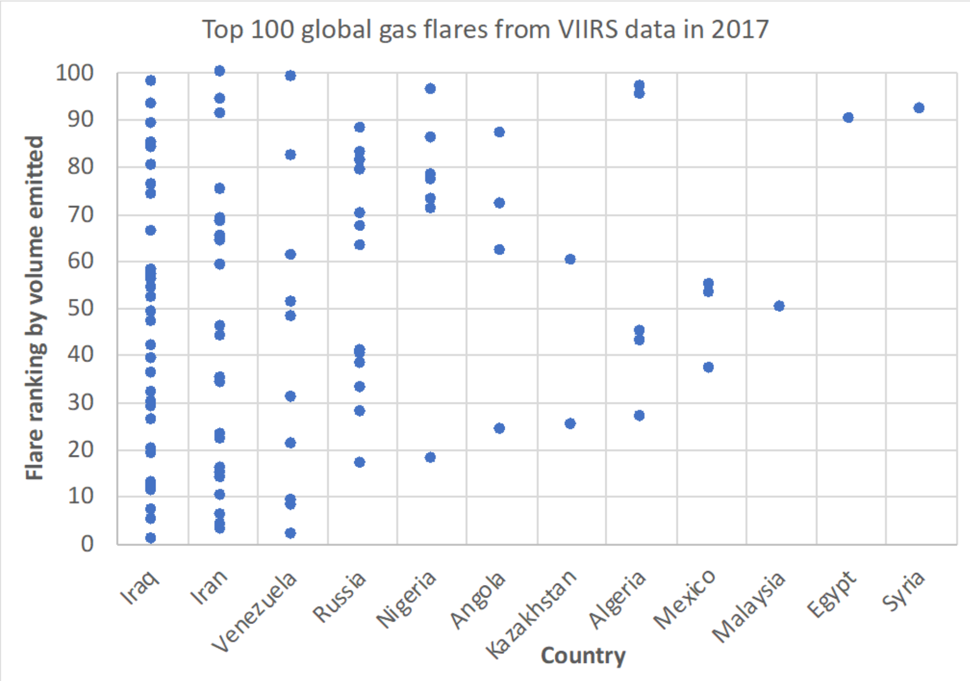
Table 1: Top 100 gas flares in 2017, as identified by VIIRS

	Number of flares in the global top 100	Top 100 flares per country
Iraq	31	1, 5, 7, 11, 12, 13, 19, 20, 26, 29, 30, 32, 36, 39, 42, 47, 49, 52, 54, 56, 57, 58, 66, 74, 76, 80, 84, 85, 89, 93, 98
Iran	22	3, 4, 6, 10, 14, 15, 16, 22, 23, 34, 35, 44, 46, 59, 64, 65, 68, 69, 75, 91, 94, 100
Venezuela	10	2, 8, 9, 21, 31, 48, 51, 61, 82, 99
Russia	13	17, 28, 33, 38, 40, 41, 63, 67, 70, 79, 81, 83, 88
Nigeria	7	18, 71, 73, 77, 78, 86, 96
Angola	4	24, 62, 72, 87
Kazakhstan	2	25, 60
Algeria	5	27, 43, 45, 95, 97
Mexico	3	37, 53, 55
Malaysia	1	50
Egypt	1	90
Syria	1	92

Note: as an example of a top-100 flare, the second-largest global flare in 2017, located in Venezuela, is shown in Figure 5.

Source: authors' construction based on NOAA VIIRS data.

Figure 4: Top 100 gas flares in 2017, as identified by VIIRS

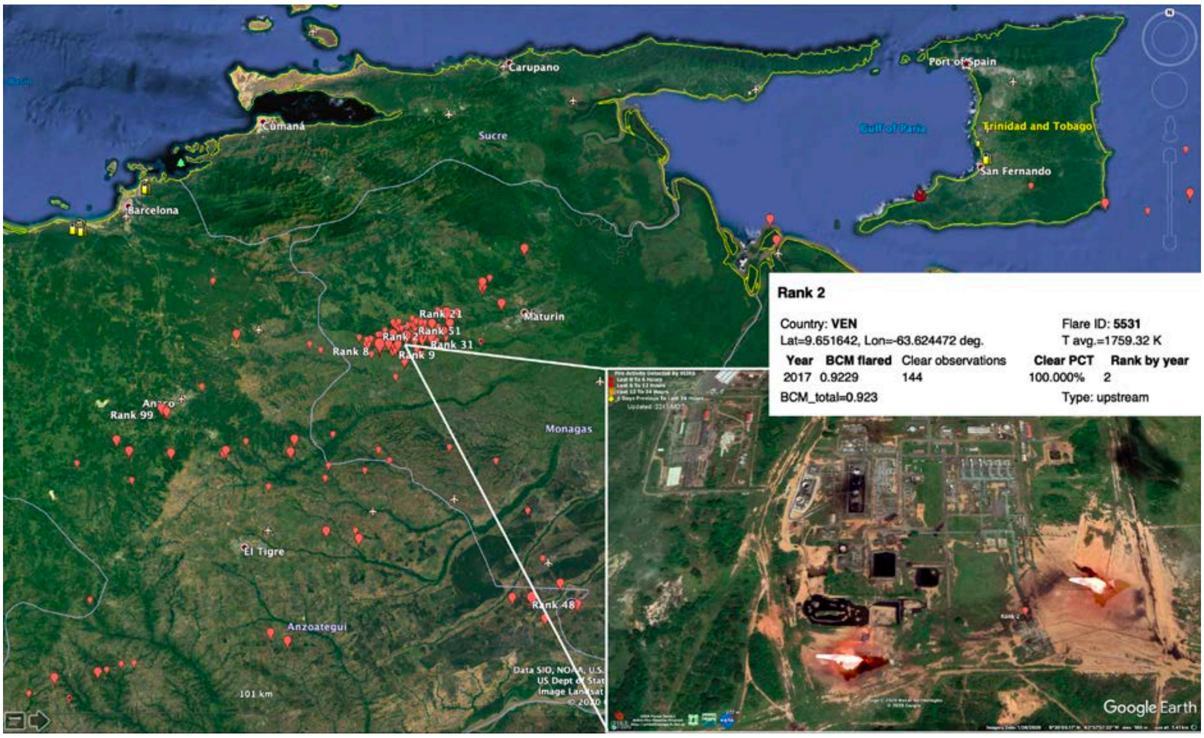


Note: Iraq has the most flares in the top 100, followed by Iran and Venezuela; the top four countries with the greatest flaring volume are Russia, Iraq, Iran, and the US, respectively (Romsom and McPhail 2021).

Source: authors' illustration based on NOAA VIIRS data.

VIIRS determines flare rates from emitted light and heat. If the flare quality is bad and the flare is emitting a lot of smoke, this can partially obscure the flare and so influence the volume estimate. Therefore, once VIIRS has identified flare locations, it is good practice to get complementary information on flares by remote sensing from other satellites, such as data from the OMI (Ozone Monitoring Instrument) on board NASA's Aura satellite. Combining sensor input not only provides more accurate rate estimates, but can also provide a detailed picture on individual chemical releases that determine flare quality and SCAR. Appendix A gives an overview of individual gas flares detected by VIIRS. It should be noted that in addition to routine flaring to dispose of natural gas as a waste product, many other flares are installed as emergency devices to divert natural gas and perform blow-down of oil and gas facilities to safely respond to operational upsets. Such flares emit occasionally high flare rates for short periods of time.

Figure 5: Identification of the second-largest flare globally, in Venezuela



Note: this Venezuelan flare burned an estimated 0.92 bcm of natural gas in 2017, accounting for 13% of natural gas flared in Venezuela and 0.66% of global natural gas flared that year.

Source: authors' illustration based on a combination of Google Earth images with 2017 VIIRS data.

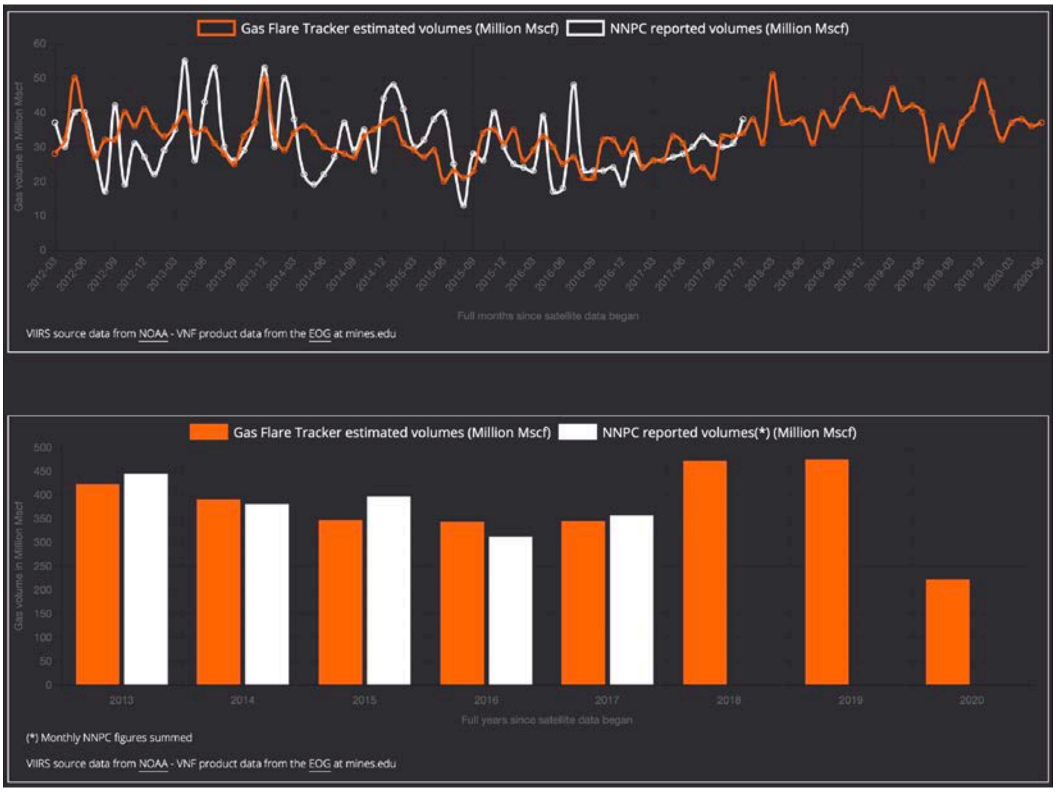
3.3 Gas flaring tracker in Nigeria

With an estimated flaring volume of 7.8 bcm per year, Nigeria ranks globally as the seventh-largest gas flaring nation. However, it has made remarkable progress in creating a Gas Flare Tracker that assesses flaring sources across the country based on daily VIIRS satellite data. Historically, these data have been very difficult to compile because of the multitude of sources, the geographical distribution, and difficulty of local access. A key driver for the Nigerian government in developing the Gas Flare Tracker is the potential tax income levied on the oil and gas companies based on their volume of gas flared. Comprehensive and accurate measurement of flaring data by source and owner is therefore a key objective for the government of Nigeria. The flaring data are publicly available on a website,[4] displaying a map of all of the gas flares in the region, with details per asset and over time on gas being flared. The potential for alternative use for the Nigerian gas currently flared is substantial: close to 28,000 gigawatts of power could be generated, which could provide 40 per cent of Nigeria's electricity demand. This is particularly relevant in Nigeria, where reliable, round-the-clock electricity is generally lacking. Measuring gas flared and taxing the flaring companies is a key step to disincentivizing flaring and promoting alternative use of natural gas. However, other hurdles would need to be overcome to aggregate the APG and make the required infrastructure and power investments. More stringent enforcement of tax collection and fines is also needed.

Nigeria's gas flaring tracker was developed with support from the UK's Department for International Development and is being managed and maintained by Nigeria's National Oil Spill Detection and Response Agency (NOSDRA). Part of the effort to establish a reliable gas flaring tracker for Nigeria was the development of a reliable method of calibrating reported and satellite-observed flare data (Hodgson 2018). Although this type of calibration has been carried out in the past and methods used are well documented, the Nigeria study was the first to use many ground-sourced, monthly gas flare data points (280) from the Niger Delta to try to create a calibration that works on both local and regional levels. Inputs to the satellite calibration were the reported flare volumes supplied by oil companies to the Nigerian National Petroleum Corporation (NNPC). Although the NNPC dataset was imperfect, a scalable calibration equation was devised using VNF data. Errors in the flaring estimates correlate strongly with the number of data observations. Intermittent or irregular flares, and the presence of clouds, can affect the number of VNF data points to support the flaring estimates. Multi-satellite and multi-sensor data can significantly reduce these uncertainties, as well as improving the calibration methodology by addressing the impact of flare quality on flare volume assessments (see Figures 6, 7, 8, and 9).

[4] See https://nosdra.gasflaretracker.ng and https://gasflaretracker.ng.

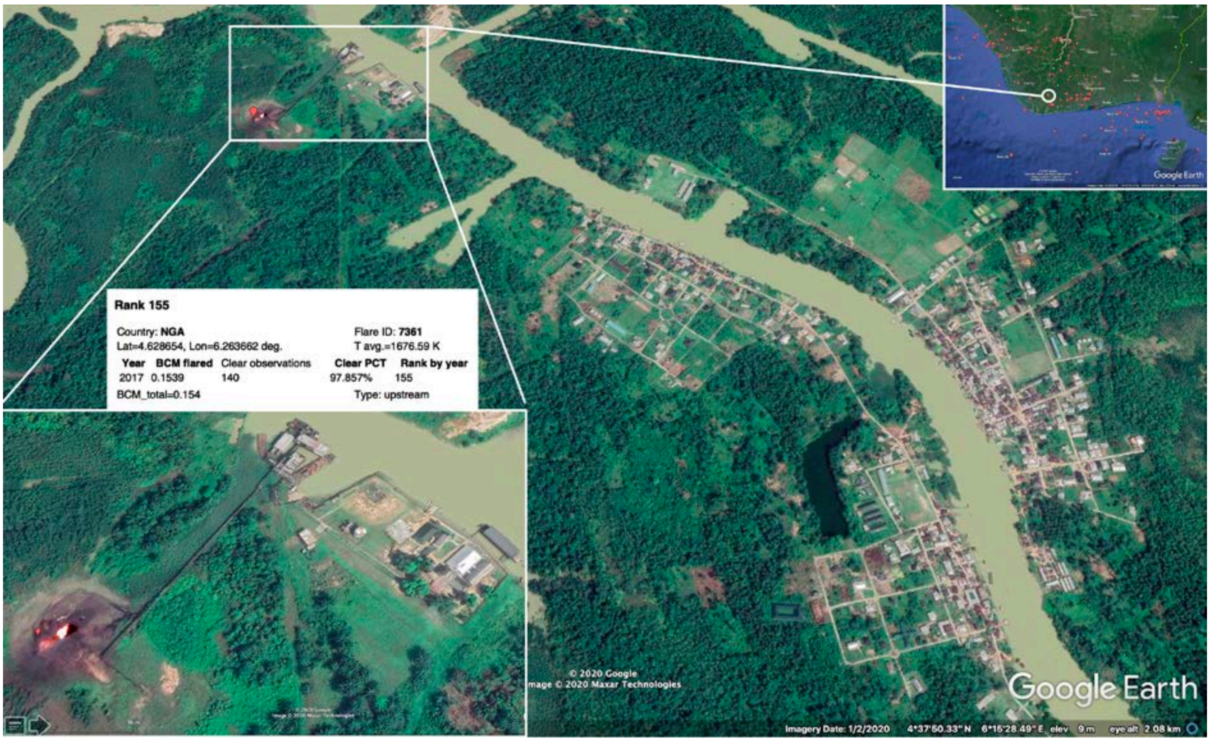
Figure 6: Comparison of reported and VNF-estimated flare data in Nigeria



Note: the NOSDRA Gas Flare Tracker provides good average comparison between estimated and reported flare volumes. However, VNF data occasionally fail to pick up short-term trends in reported flare data. This could be due to lack of data (e.g. cloud overcast), high-smoke flares obscuring the flame, or other flare quality issues.

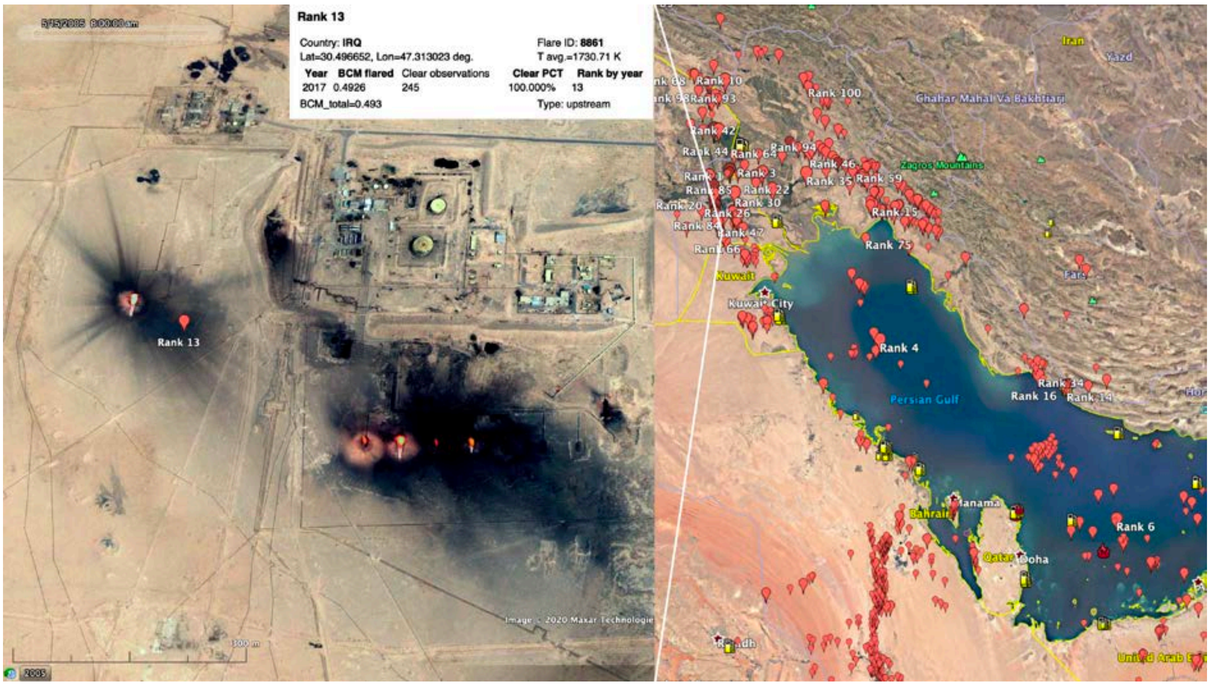
Source: NOSDRA (National Oil Spill Detection and Response Agency). This figure is reproduced here under fair use for research, knowledge-sharing, and educational purposes.

Figure 7: Identification of a flare (ranked 155th) near a village in the Niger Delta in Nigeria



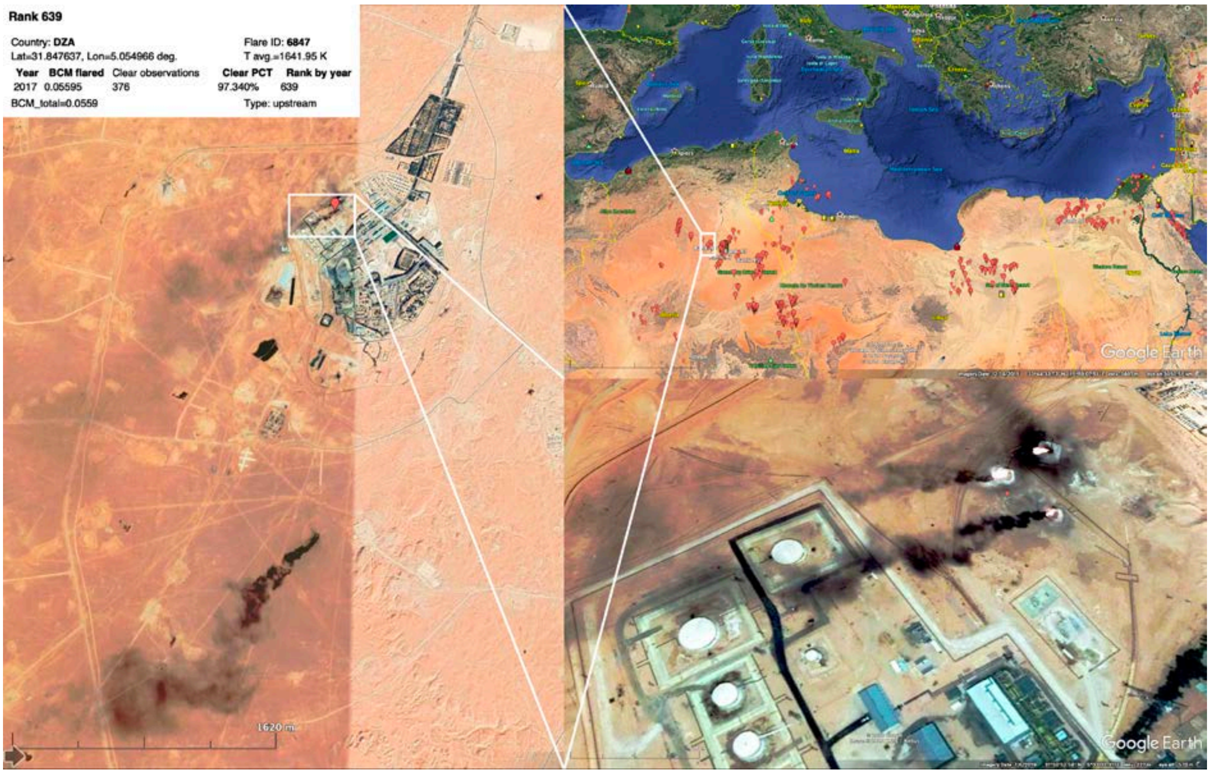
Source: authors' illustration based on a combination of Google Earth images with 2017 VIIRS data.

Figure 8: Identification of a super-emitter flare, located in Iraq



Source: authors' illustration based on a combination of Google Earth images with 2017 VIIRS data.

Figure 9: Example of smoking flares in Algeria, ranked 639th in 2017

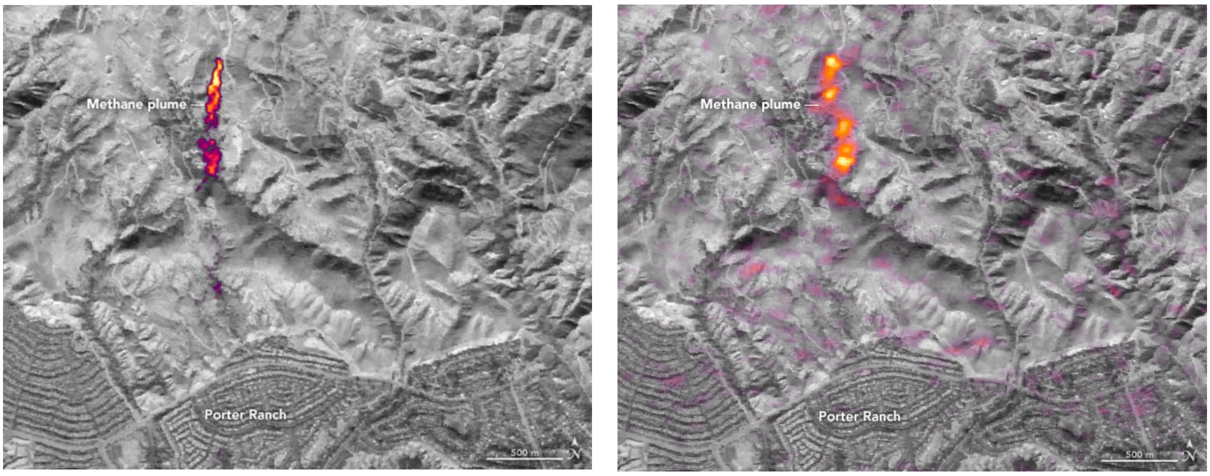


Source: authors' illustration based on a combination of Google Earth images with 2017 VIIRS data

3.4 Remote sensing by satellites to assess natural gas venting

The estimation of methane emissions through leaks or deliberate venting of natural gas has historically been hampered by a lack of accuracy in estimates, with a discrepancy between bottom-up and top-down estimates. Bottom-up methodologies are based on point sources and deliver higher accuracy per source point, yet they may fail to identify all point sources. Top-down estimates determine the amount of methane in a larger area, yet they may wrongly assign such volumes to certain assets, thereby overestimating the amount of release by these assets. In our first flaring report, we provided additional information on the importance of the combination of higher accuracy and more comprehensive data-gathering on methane releases. Recent improvements in satellite detection equipment may now start to identify methane emitters with higher spatial accuracy and across larger areas. The first time a satellite was able to observe a high-resolution methane release and attribute this detection to a single facility was in 2016 (see Figure 10). Since then, satellite capabilities have improved further. On 2 September 2020, GHGSat launched Iris, a new satellite to measure methane emissions with a spatial resolution of 25 m and a field of view of 25 × 25 km. Iris is a similar but much improved version of satellite GHGSat-D Claire, a technology demonstration satellite that was launched in 2016. Claire, with an orbit of 90 minutes, is able to evaluate a thousand sites per year. Iris is expected to provide a factor-ten performance improvement. An example of Claire's capabilities was published in November 2019 (Varon et al. 2019), highlighting large and persistent methane emissions near oil and gas installations of the Korpezhe field in western Turkmenistan near the east coast of the Caspian Sea, during the period November 2017 to January 2019. The estimated amount of methane released in this period was 142 ± 34 metric kilotons.

Figure 10: First satellite detection of a methane plume leaking from a single facility in January 2016



AVIRIS Aircraft data - January 12, 2016

EO-1 Satellite data - January 1, 2016

Note: methane observations were made by the Hyperion spectrometer on NASA's Earth Observing-1 (EO-1) satellite (right) and are compared with AVIRIS aircraft data (left), at an underground natural gas storage facility near Aliso Canyon, California.

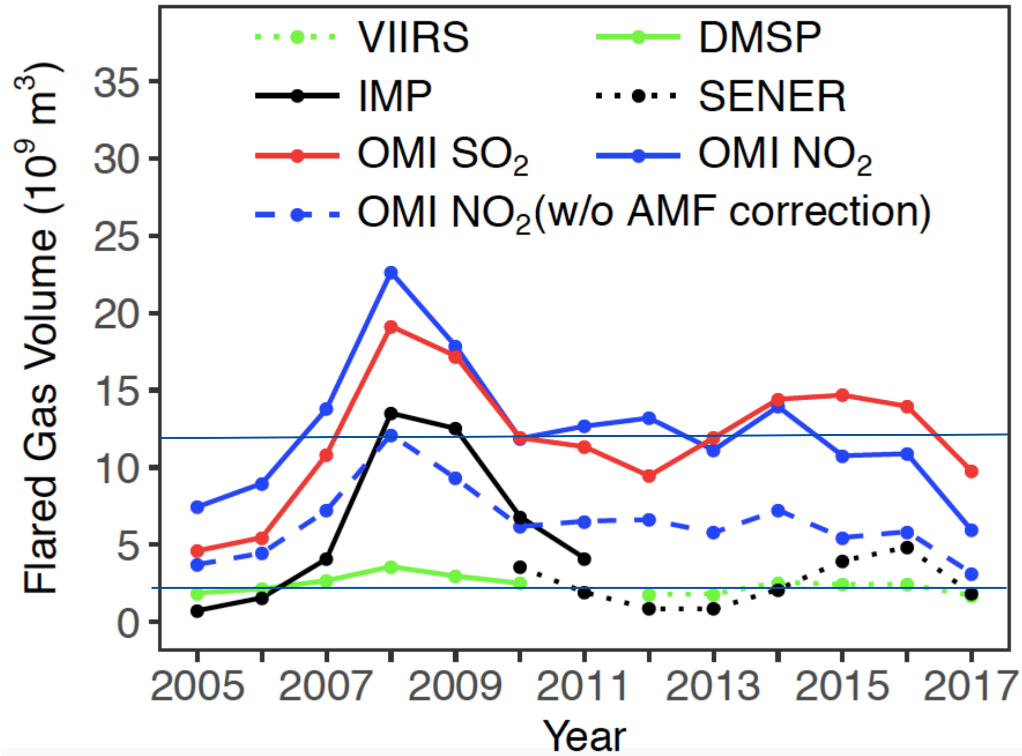
Source: NASA's Earth Observatory, with permission: https://earthobservatory.nasa.gov/images/88245/imaging-a-methane-leak-from-space.

NASA's EO-1 and GHGSat-D's observations exemplify the potential of satellite detection technology to improve on the identification and measurement of oil and gas sources of atmospheric methane releases with high spatial and spectral accuracy.

3.5 Systemic under-reporting of atmospheric emissions

Under-reporting of flaring and venting appears to be a systemic issue in the industry. Without reliable data, the development of flaring and venting reduction solutions is being hampered. For example, a study into APG flaring in Russia, Kazakhstan, Turkmenistan, and Azerbaijan (Haugland et al. 2013) observed that satellite data exceeded reported flaring in Russia (the world largest flaring country) by more than a factor of three in 2005. In 2011 this discrepancy had reduced but was still just above a factor of two. In this same period, Kazakhstan (then ranked seventh-largest flaring country) under-reported with a discrepancy that increased from a factor of two in 2006 to a factor of four in 2011. A recent study on onshore flaring in Texas (Willyard and Shade 2019) concluded that self-reported flaring volumes underestimate actual volumes by a factor of two, a result that is consistent with other studies (Collins 2018; Leyden 2019). Another recent study on flaring in the period 2012–18 compared government-reported flaring data for offshore oil and gas installations in nine countries (Brazil, Canada, Denmark, Mexico, Netherlands, Nigeria, Norway, UK, and USA Gulf of Mexico) with radiant heat observations from VIIRS (Brandt 2020). The study concluded that there was no overall bias when all data were combined, although variations in reporting between countries and over time do occur. In another study on flaring in offshore Mexico (ranked tenth among the largest flaring nations), satellite data were compiled and a multi-pollutant analysis used to compare top-down estimates with bottom-up flaring assessments and reporting (Zhang et al. 2019). In this latter study, OMI data from on board NASA's Aura satellite were used to track NO_2 and SO_2 emissions from offshore oil and gas installations in Mexican waters in the Gulf of Mexico. These were compared with radiant heat observations from the Defense Meteorological Satellite Program (DMSP) and VIIRS, and data from the Emission Database for Global Atmospheric Research (EDGAR), Instituto Mexicano del Petróleo (IMP), and Secretaria de Energia de México (SENER). Figure 11 shows a comparison of these individual flared gas volume assessments in a single graph.

Figure 11: Reported versus satellite measured flaring data in Mexico



Source: reproduced from Zhang et al. (2019), under the Creative Commons license CC BY-NC-ND 4.0.

This analysis not only confirms the need to improve on flaring measurements and reporting: the study also shows the benefits of multi-pollutant analysis and the combination of multiple satellite sensors to reduce uncertainties in estimates. The authors reported that the SO_2 emissions were completely missing from the EDGAR database and the NO_2 emissions were included only in the recent EDGAR update, albeit at a factor of ten lower than the satellite estimates. The trends in OMI emission data for NO_2 and SO_2 appear to track the government reported IMP/SENER data, but with reported flaring rates a factor of two less than those derived from OMI data. In this case, the radiant heat data from DMSP/VIIRS appear to significantly underestimate OMI data by a factor of five, as well as the reported IMP/SENER data. The radiant heat data also appear to have missed the spikes in flaring emissions in 2008 and 2015/16.

The combination of flare gas metering, wellhead fluid sampling, and OMI/VIIRS/Landsat remote sensors provides **opportunities for increased accuracy in calibration methods to link satellite data to flare volume estimates**. Moreover, as discussed in our first report on flaring (Romsom and McPhail 2021), it is not only the magnitude of flaring that is important but also the quality of the flaring process. Many impact assessments assume (near) perfect combustion of natural gas by flaring, although in practice there are repeated observations of flares that do not meet these conditions. This results in atmospheric releases of chemicals that have a significantly greater SCAR per ton than CO_2 or methane (see Figure 1). The ability to measure individual releases and establish reliable correlations between releases—such as between NO_2 and BC (Li et al. 2016)—enables **SCAR estimates that account for both the volume and the quality of natural gas flaring**. Satellite observations also provide valuable information on the transportation of atmospheric releases, enabling assessments to be made that determine geography-dependent risks (such as population density and exposure of the Arctic region to BC).

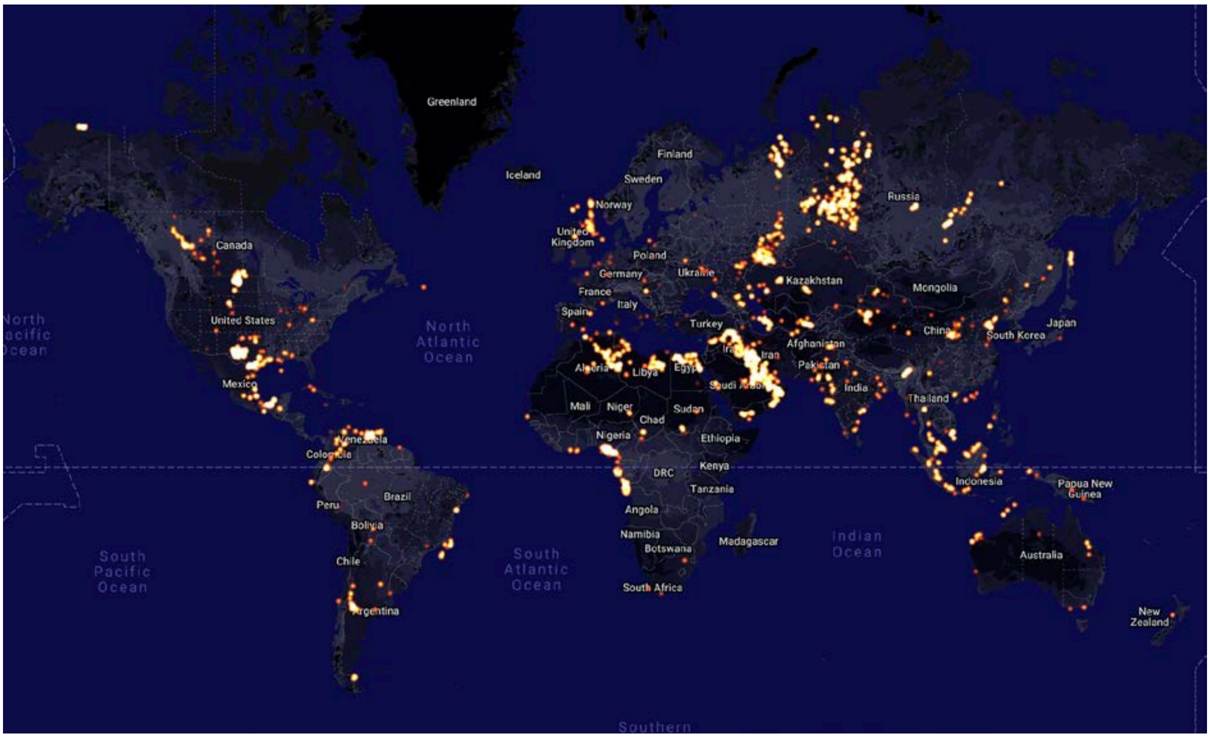
Operators—and sometimes also regulators (Haugland et al. 2013)—may benefit from not reporting or under-reporting natural gas flared and vented. These benefits can be financial (avoiding fiscal taxes, fines), commercial (avoiding costs of proper gas treatment) and reputational (avoiding non-compliance with quality standards, being earmarked as a polluter, or negative social impact due to degrading air quality). However, without accurate reporting and transparency thereof, there is less incentive to improve on detrimental emission practices. Furthermore, regulators may lack the necessary data to enforce compliance with applicable rules and regulations by oil and gas operators. The third-party certification of vent and flare emission data (see Section 4.2) provides a level of commonality, quality, and reliability that these can be trusted and utilized.

In conclusion, reliable assessment of emission streams from flaring and venting serves a variety of purposes:

- it improves understanding of how much natural gas is emitted and lost through these practices and thereby helps to determine the basis for assessing both compliance with emission volume restrictions and any taxes and/or fines that may be levied;
- it can provide reliable estimates on the volumes of individual chemicals emitted to determine the SCAR of each flare and vent;
- it can help determine if the flare is operating within its design envelope, i.e. if the targeted destruction efficiency of 98 per cent is being met (EPA OAQPS 2012);
- it can identify potential super-emitter flares and vents early for corrective action;
- it can support the calibration of local data with remote satellite observations and further develop transport models to assess the regional distributions of SCAR;
- it can provide a baseline dataset as input to potential investments to aggregate, process, and utilize natural gas for economic use.

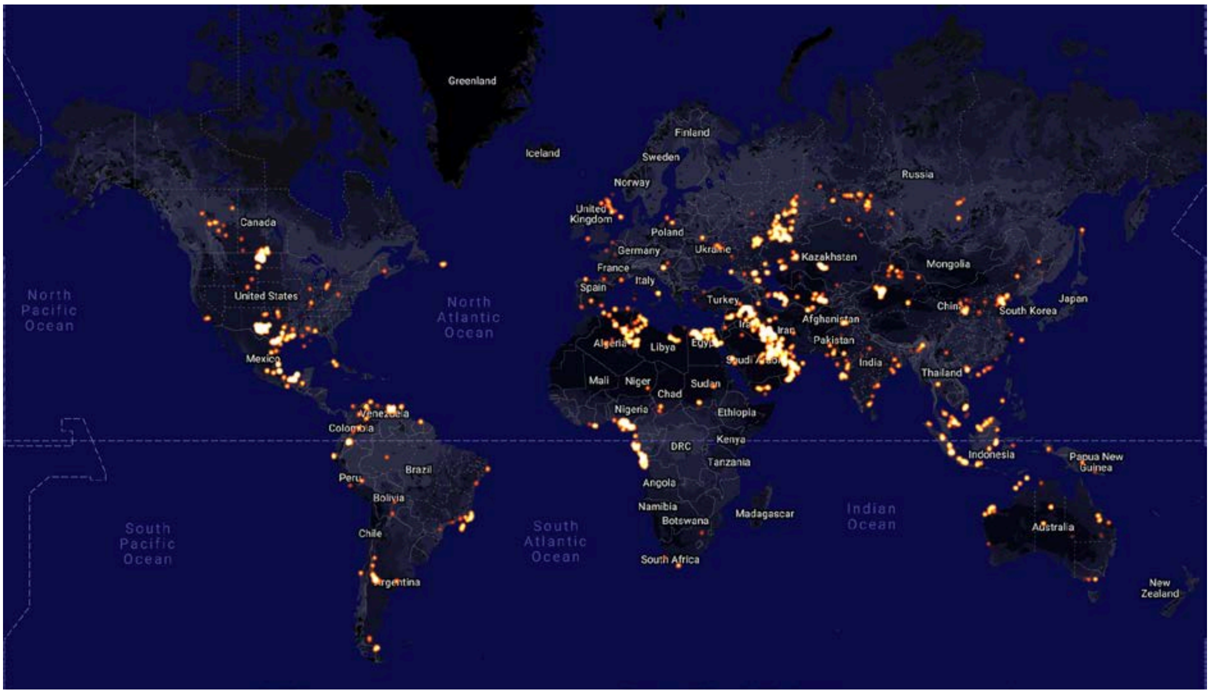
Further detailed information and interactive maps to assess sources of gas flaring can be found on the SkyTruth website (https://skytruth.org/viirs/); see also Appendix A for more information on global locations where natural gas is flared. Figure 12 shows a comparison of global gas flaring on 1 January 2020 and 30 June 2020.

Figure 12a: SkyTruth image of global flaring sites on 1 January 2020

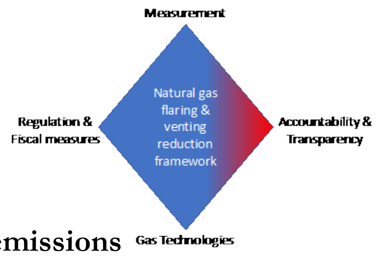


Source: reproduced with permission from SkyTruth, ‘Flaring Maps’.

Figure 12b: SkyTruth image of global flaring sites on 30 June 2020



Source: reproduced with permission from SkyTruth, ‘Flaring Maps’.



4 Accountability, transparency, and reporting of venting and flaring emissions

4.1 Global gas flaring and venting reduction initiatives

More effective measurement is the first component of the Diamond model. The use and enhancement of measuring systems to introduce improved reporting, enhanced accountability, and greater transparency represents the second component. Initiatives in this area—already in operation or proposed—are the subject of this section.

Global gas flaring and venting reduction initiatives: key points

- Since 2002, there have been a number of voluntary global multi-stakeholder initiatives to reduce upstream flaring and venting.
- The focus is principally on standards, improvements in measurement, and commercialization. There is less emphasis on fiscal measures.
- There was some reduction in gas flaring between 2004 and 2014. The combined amount of gas flared and vented between 2000 and 2017 stayed relatively constant. Flaring reduced in absolute terms while venting (methane) increased.
- Flaring data assume a 100 per cent combustion efficiency—where all hydrocarbons are destroyed. Many flares do not reach this target and produce a range of chemicals that are toxic to human health, as well as affecting air quality and climate.
- Methane emission avoidance is a major opportunity to reduce short-term impact on global warming and, more importantly, on human health.
- More recently, institutional investors have focused on how to reduce climate risk to their portfolios by engaging with oil and gas companies to measure, manage, reduce, and disclose methane emissions.
- Concerted action is needed by all emitting companies, including those not participating in any voluntary initiatives. Non-voluntary measures (i.e. regulation) are needed to reduce flaring and venting.

The Global Gas Flaring Reduction (GGFR) public–private partnership was launched by the World Bank and the government of Norway at the World Summit on Sustainable Development in Johannesburg in 2002 (GGFR 2019). Based on early joint work (IGU Magazine 2013–14), which showed that global flaring levels had remained virtually constant since 1980, the aim was to catalyse the public and private sectors to reduce carbon emissions and environmental impact of flaring, monetize a wasted resource, and improve energy efficiency and access to energy.

GGFR uses the following definition for routine flaring, the target for reduction: 'Routine flaring of gas is flaring during normal oil production operations in the absence of sufficient facilities or amenable geology to re-inject the produced gas, utilize it on-site, or dispatch it to a market.' All other flaring, even when continuous, is considered non-routine or safety flaring.

This means that a number of oil production operations are not part of the scope of the GGFR programme, e.g. flaring due to system upsets and emergency operations, maintenance activities, well clean-up and production well tests, exploration well (deliverability) tests, and gas influx into the wellbore during drilling operations

However, the GGFR scope does include gas flaring during oil production for commercial reasons or due to lack of gas processing and evacuation infrastructure, and these are to be eliminated. For this effort to be successful and to avoid abuse, stringent definitions of 'routine flaring' and 'normal production operations' need to be agreed and adhered to.

Actions have included improved measurement and transparency; regulations and standards; and market opportunities:

International: joint work with the US NOAA to improve continuous measurement of flaring using satellite data covering 60 countries.

National governments: support to low- and middle-income countries for oil and gas legislation (World Bank 2004; Svensson and Rios 2012); seek market opportunities for associated gas (GGFR 2009), including technologies for the commercialization of small volumes of associated gas, such as CNG (compressed natural gas), mini- and micro-LNG (liquified natural gas), and GTL (gas-to-liquids).[5]

Companies: a Voluntary Global Standard (GGFR 2004) and guidelines on flare and vent measurement, to ensure no flaring in new projects and to eliminate continuous production flaring in five to six years.

GGFR reported that its contributions to flaring reductions by 2013 included (GGFR 2013):

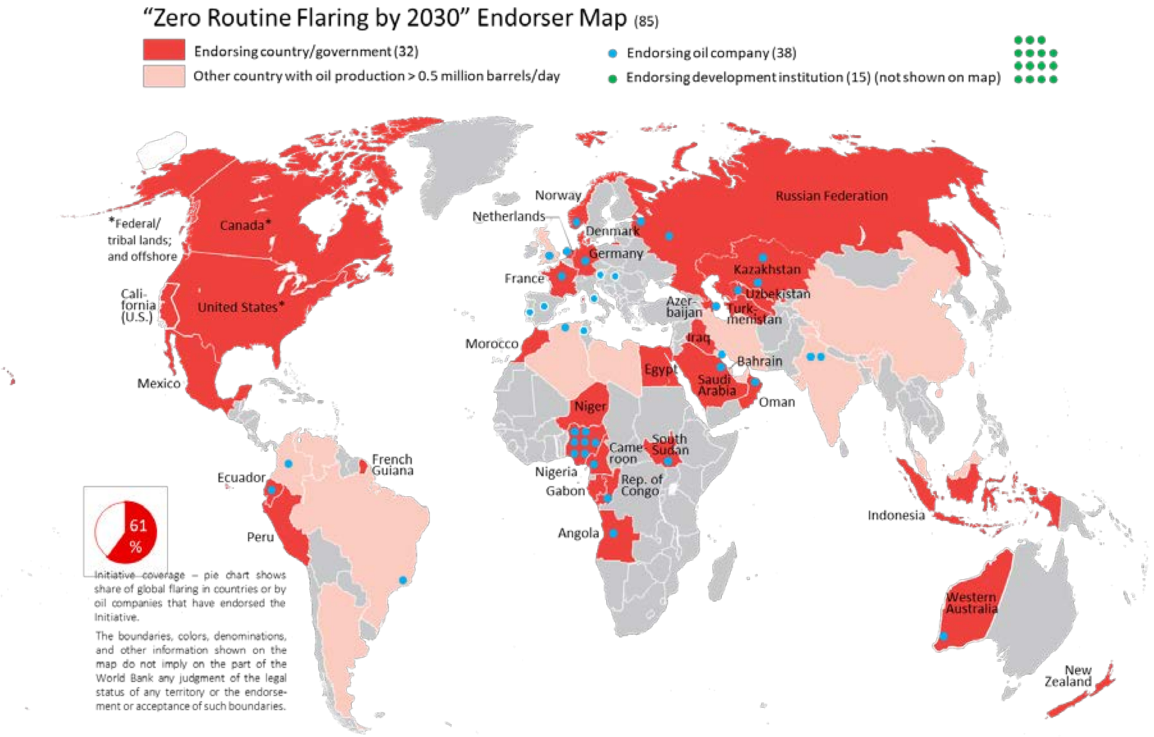
- gas flaring reduced by 20 per cent from 154 bcm in 2007 to 140 bcm in 2011;
- regulations on gas flaring passed in Russia, Angola, Kazakhstan, Gabon, and Cameroon, and under development in Indonesia, Nigeria, Qatar, and Iraq;
- gas utilization projects developed in Angola, Cameroon, Gabon, Nigeria, Kazakhstan, Qatar, Russia, and Uzbekistan.

After 2013, momentum slowed; this led to a rekindling of the flaring reduction efforts by the World Bank Group in 2015, when the 'Zero Routine Flaring (ZRF) by 2030' initiative was launched. However, as Figure 14 shows, flare volumes continue to rise in several large flaring countries (GGFR 2020b).

The ZRF initiative is currently endorsed by 32 governments, 38 oil companies, and 15 development institutions and supported by OPEC; see Figure 13. Although the initiative has more endorsers than GGFR has partners, not all GGFR partners have endorsed ZRF. In particular, Algeria, Kuwait, Qatar, Chevron, ExxonMobil, Pemex, and Qatar Petroleum have yet to endorse ZRF and adopt its targets.

[5] GTL technology is based on a gas -refining process to convert natural gas or other gaseous hydrocarbons into liquid synthetic fuels with longer-chain hydrocarbons, such as gasoline or diesel fuel.

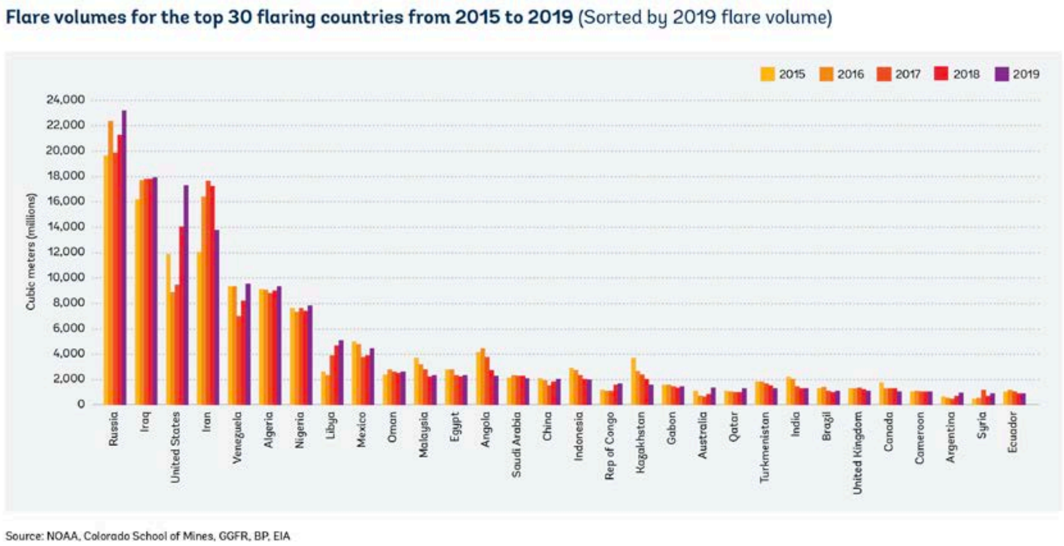
Figure 13: Endorsers of 'Zero Routine Flaring by 2030'



Source: reproduced from World Bank (undated). The World Bank Group authorizes the use of this material subject to the terms and conditions on its website, Legal.

An important accomplishment is the development of satellite measurement data. By 2019, there were more than 100 countries with satellite flare data, which is summarized and published by GGFR on an annual basis. Where flare operational performance does not meet quality standards, chemicals are emitted such as NO_X, SO_X, VOCs, and BC, each of which have a significantly larger SCAR per ton than either CO_2 or methane. This negates most of the benefits that flaring has over venting. Thus, there is an immediate opportunity to improve the quality of flaring to avoid 'super-emitter flares'.

Figure 14: GGFR and 'Zero Routine Flaring by 2030' initiatives need further efforts to reverse the trend of increasing flare volumes



Source: reproduced with permission from GGFR (2020a), *Global Gas Flaring Tracker Report*.

In parallel, global initiatives were launched on methane emissions reduction, focusing initially on capturing value and developing policies and regulation. Measurement came much later. The first, Methane to Markets in 2004, was launched with 14 governments led by the US and focused on **methane abatement, recovery, and use**. In 2010 it was renamed the Global Methane Initiative (GMI),[6] and it has 44 countries and the European Commission as members. There is also a GMI network of more than 700 project network members, mostly from private sector companies but also including financial institutions, research/academia, NGOs, and others, sharing experience and expertise across the network for methane emissions reduction. The network has helped GMI to leverage nearly US$600 m in private sector and financial institution investment for projects that capture and use methane.

In 2017, the Methane Guiding Principles (MGP),[7] a multi-stakeholder platform of 20 institutions from industry, academia, and intergovernmental organizations, including the IEA, was set up to develop **methane policy and regulation**.

In 2018, international oil and gas companies, members of the Oil and Gas Climate Initiative (OGCI) set a **target to reduce methane intensity** in upstream oil and gas operations from 0.32 per cent in 2018 to 0.25 per cent by 2025 (OGCI undated). The UN Principles for Responsible Investment (UNPRI), which in 2020 represents about 3,000 investors with over US$100 trillion in assets under management, recommended in 2015 that international oil companies (IOCs) should extend their standards on methane emissions to non-operated joint venture partners and state-owned companies. The OGCI target covers operated assets only, thus missing an opportunity to speed up reduction of methane emissions by applying the target to all company operations. Methane intensity figures are useful, particularly in comparing and benchmarking companies and countries on their methane performance. However, with respect to SCAR impacts and climate change mitigation under a limited global carbon budget, absolute reduction measures are more practicable.

Another voluntary multi-stakeholder platform, the Oil and Gas Methane Partnership (OGMP), created by the Climate and Clean Air Coalition (CCAC), was launched at the UN Secretary General's Climate Summit in New York in September 2014. It focuses on **emissions measurement**. The ten partner companies are BP, Ecopetrol, Eni, Equinor, Neptune Energy International SA, Pemex, PTT, Repsol, Shell, and Total. In January 2020, OGMP members agreed to an updated **framework for reporting methane emissions** transparently to civil society and governments (CCAC undated [a]). This includes that companies report all material sources of methane emissions from operated and non-operated assets. Member companies are to publish individual reduction targets and report on progress. In 2019, the CCAC launched the Global Methane Alliance (GMA) to support countries that commit to ambitious **methane reduction targets** in the oil and gas sector through methane solutions that promote economic development, air quality improvement, and other country priorities (CCAC undated [b]).

Another initiative focused on **methane measurement** was launched in 2018 by global investors Ceres, members of the UNPRI (Ceres 2018). It provides guidance to oil and gas companies and their investors on how to apply the Task Force on Climate-Related Financial Disclosures (TCFD) framework for **disclosure on methane emissions**, with a suggested implementation timeline.

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[6] See https://www.globalmethane.org.

[7] See https://methaneguidingprinciples.org.

These global initiatives have a common theme in that they are all voluntary. The World Bank GGFR publishes flaring data for 86 countries but is silent on the issue of venting gas. Parties that are not part of the World Bank initiative are under no obligation to report their flaring and venting contributions. The IEA online database for methane emissions reports in $MtCO_2e$, although this obscures the non-global-warming-related damages from methane and damages from other hazardous air pollutants (such as VOCs) when natural gas is vented.

Although the objective in emissions reduction is the same, concerted action by all emitting companies is needed, including those not participating in any of the groups mentioned here. Regulation and fiscal measures—complementing improvements in measurements as opposed to relying on estimates—data transparency, and technical solutions are needed to drive the industry in lowering their fugitive emissions.

As set out in Section 3, there has been little reduction in the volume of gas flaring and venting in recent years: 6.9 per cent of globally produced natural gas is flared (3.7 per cent) and vented (3.2 per cent) in upstream oil and gas operations. Global flaring and venting volumes are significant both in terms of opportunity costs and from the perspective of social costs such as impact on human health, air quality, and climate.

4.2 Company and country reporting, and transparency and accountability initiatives

4.2.1 Reporting of venting and flaring emissions

Reporting and transparency: key points

- Measurement and public reporting of both flaring and venting are variable and need improvement. Institutional investors and financial regulators are now focused on addressing this gap, for example with the standard framework of the TCFD. Also, climate metrics now include upstream hydrocarbon flaring and venting.
- Mandatory company reporting is more effective at reducing emissions (including GHGs). It produces comparable data which enable benchmarking, peer pressure, performance improvement, and an assessment of climate and health risks.
- Transparency and accountability benefits companies' licence to operate, improving its social licence to operate, access to capital, and access to markets.
- The Nigeria Gas Flare Tracker is an example of an open source database which allows government, citizens, and community organizations to have visibility over the full scale of the flaring events, potential value for the country, and opportunities to capture APG for health, economic, and social benefit.

Improvements needed for reliable flaring and venting data

The measurement of fugitive emissions, including flaring and venting, is difficult in the absence of accurate metering. Often, little information is available on flare properties that can improve operational performance and reduce social and environmental impact. Shortcomings in the data on emissions from natural gas flaring and venting are caused by the following:

At the company level, gas that is being flared or vented is most often not metered and therefore flare data are estimates at best (for example based on flare size and colour). Much of the existing flaring data relies on self-reporting. Therefore, flare measuring/estimation standards are likely to vary significantly between parties and, without a verification process, can be under-reported. The reporting format varies across companies, which makes comparison and benchmarking difficult.

The measurement of air quality is often not part of a mandatory regulatory scheme. In an collaborative effort coordinated by the UNPRI to persuade companies to measure, manage, and reduce their methane emissions, 36 global institutional investors, representing approximately US$4.2 trillion, engaged with 31 oil, gas, and utilities companies over a three-year period (UNPRI 2020). They found that corporate efforts to properly track and manage methane leaks remain weak, exposing investors to significant risk both at the company level and across their portfolios due to the associated impact on the climate and health.

For governments, local regulations for measuring flaring and venting are often non-existent or not enforced. Many governments do not distinguish routine flaring from total flaring in their data. There is, however, ambiguity in the definition of routine flaring and what is reported (or not reported) under that category. For example, a long-term exploration gas well test is unlikely to be considered routine flaring. Third-party assessment is important to improve data reliability and reporting consistency. Solutions to address these issues are discussed in more detail below.

Variability in measurement and reporting

Companies. The industry-led TCFD has recognized the **need for standardized data, including on upstream flaring and venting**, to understand how energy companies are managing climate risks both to physical assets and to the energy transition. Established by the G20's Financial Stability Board (FSB) in 2015, it was set up to develop disclosures that enable a consistent assessment of companies' and financial services' exposure to material climate risk in a unified way.

In 2017, the TCFD published a framework for reporting. There are four recommendations for disclosures, namely on strategy, governance, risk management, and climate metrics. It recommended that this framework be applied in a uniform way across all sectors and financial services. Energy companies are to disclose GHG emissions, including gross global Scope 1 emissions. These are expected to drive regulations (including carbon prices) that require lower emissions from products. These transparency measures introduce new areas of competitiveness for companies to strengthen their value proposition to customers and to society. Other climate metrics included in the framework are intended to disclose the current internal carbon price or range of internal prices used.

The TCFD climate metrics for hydrocarbon flaring and venting include emissions from:

1. combustion;
2. flared hydrocarbons;
3. process (including transport) emissions;
4. directly vented releases; and
5. fugitive emissions/leaks.

The TCFD does not develop detailed, industry-specific metrics. Instead, it references existing standards that companies can use to identify the climate-related risks and metrics most relevant to their industry. The Carbon Disclosures Standards Board Framework and the Sustainability Accounting Standards Board standards are among the most frequently cited. In 2018, the UNPRI and two NGOs published a guide for oil and gas companies and their investors on how to apply the TCFD framework for disclosure on methane emissions (UNPRI et al. 2018).

In January 2020, OGMP members agreed that companies should report actual methane emissions data from operated and non-operated assets, and to progress towards source-level and site-level measurements within three to five years.

Although the social impact of flaring and venting exceeds climate-related damages, the frameworks of the TCFD and the OGMP are valuable to improving transparency on these emissions. This increased transparency will further benefit action to also address health and other social impacts from flaring and venting.

National governments/EU and companies

Local regulations for measuring flaring and venting are often non-existent or not enforced.

Mandatory vs voluntary reporting. In many countries, reporting is voluntary. The TCFD recommends that disclosures be included in companies' public annual filings to provide 'decision-useful' information to investors and other financial services. In its 2019 Annual Report, the TCFD noted that transparency has made undeniable but insufficient progress. In May 2020, Mark Carney noted that while the support for the TCFD has risen globally, the voluntary framework has not yet produced comprehensive data: 'That goes to part of the reason why we think it is now time for mandatory disclosure' (Johansson 2020). Global institutional investors, members of the UNPRI, are planning to engage policy-makers on the need for strengthened methane disclosure rules and robust pricing of methane emissions as part of carbon pricing systems.

Reporting on GHGs by listed companies has been mandatory in the UK since 2013 when the Companies Act 2006 was amended. In 2018, the UK introduced expanded regulations (Streamlined Energy and Carbon Reporting) effective 1 April 2019. Mandatory disclosure of climate-related risks for listed companies and large asset owners is to be implemented by 2022 and is to be in line with the TCFD, which the UK government formally endorsed in September 2017. This is part of the UK government's commitment to reach net zero GHG emissions by 2050.

Mandatory reporting has also been shown to be more effective than voluntary approaches. Recent reviews (Downar et al. 2019; Schiemann et al. 2019) have investigated whether mandatory disclosure of GHG emissions since 2013 influences UK companies' GHG emission levels. Factories affected by the reporting requirement show a reduction in their GHG emissions between 2009 and 2016 of up to 18 per cent more than those not affected by the reporting requirement. Emissions in the UK also declined more in both absolute and relative terms when compared with those in European countries where the regulation was not mandatory. The review concluded that the motivation to reduce emissions was a result of investor, stakeholder, and competitive pressures. It also provided important risk assessment information to the capital markets.

In the US, mandatory reporting enables comparison of GHG emissions across companies and this facilitates peer pressure. It also allows an assessment of how material upstream oil and gas flaring and venting operations are to total reported GHG emissions; see Table 2.

Table 2: Ten companies that reported the most GHG emissions from venting and flaring in the Permian Basin, 2019

Company – Facility name (GHGRP ID)	Total reported emissions (tons greenhouse gases)	Emissions from venting & flaring (tons greenhouse gases)	Per cent of total
Devon Energy Corp – 430 Permian Basin DEC (1008290)	1,418,802	1,111,789	78%
WPX Energy Inc. – WPX Energy Permian LLC (1009039)	1,527,561	988,717	65%
ExxonMobil Corp – XTO Energy Inc. 430 Permian Basin (1009390)	1,737,570	857,170	49%
Concho Resources Inc. – COG Operating LLC 430 Permian Basin (1009707)	1,546,922	678,995	44%
Surge Operating LLC – Surge Energy 430 Permian Basin (1013106)	588,483.6	476,843	81%
Occidental Petroleum Corp – Oxy Permian Basin – 430 (1008141)	857,912	412,765	48%
Jagged Peak Energy LLC – Jagged Peak Permian Basin (430) Operations (1012542)	617,650	386,431	63%
BHP Billiton – BPX Energy Permian Basin, AAPG Basin 430 (1008632)	673,556	368,984	55%
Resolute Energy Corp. – Resolute Natural Resources Company, LLC 430 Permian Basin (1011735)	415,819	366,072	88%
Encana Oil & Gas (USA) Inc – Encana Oil & Gas – Permian Basin (1008331)	802,725	333,016	41%

Source: authors' adaptation of Table 10 in Bernhardt and Shaykevich (2020), with data from U.S. Environmental Protection Agency, Greenhouse Gas Reporting Program, October 2019.

At the regional level, the EU is currently updating its guidelines on the non-financial reporting directive (NFRD). Currently this is non-binding. The NFRD sets out the minimum level of climate and environmental information that over 6,000 European companies must include in their annual reports. The draft new guidelines have integrated the recommendations of the TCFD. This would result in the update including meaningful minimum mandatory emissions reporting by all major European companies.

The European Commission (Barnes 2020) is developing a strategic plan to reduce methane emissions in the energy sector and enable reporting to follow the molecules across the supply chain. It is focused on improved measurement, including the possible adoption of the OGMP reporting framework, verification (building on Copernicus and other satellite data), and a focus on so called 'super-emitters' and hotspots. The Commission is also investigating regulatory avenues for controlling methane emissions.

A coalition of major investors led by the Carbon Disclosure Project (CDP) and a coalition of central banks and financial supervisors from 66 countries (the Network for Greening the Financial System, NGFS) are now asking companies to bring their reporting in line with the TCFD's recommendations. This combination of investors and financial regulators is significant for the global adoption of the TCFD recommendations in the banking industry and financial sector at large.

4.2.2 Transparency and accountability

Transparent company reporting and third-party assurance enhance companies' licence to operate. They allow financial regulators and investors to understand which companies are managing climate risk and allocate capital accordingly. This provides a 'level playing field' for governments to have an overview of future infrastructure requirements and potential gas market development. It also improves social licence to operate with local communities, consumers, and buyers, given the (disproportionate) benefits to air quality, health, and climate.

Companies

Third-party assessment is important to improve data reliability. While the TCFD does not yet require third-party assurance, companies are being encouraged to report as if it does. Public reporting through mainstream reports will enable other stakeholder groups to assess the disclosures provided.

Stakeholder groups: investors, civil society, and buyers

Investors are increasingly calling on companies, asset owners, and managers to disclose annual CO_2 emissions through the CDP, to disclose methane emissions in line with the TCFD, and to publish emissions reduction targets. While major financial centres have not yet made climate risk disclosure mandatory, some investors are looking to force disclosure through voting against the re-election of directors or companies' financial statements when carbon emissions are not disclosed. Methane disclosure is seen as an opportunity for companies to differentiate themselves with investors by demonstrating they are taking climate risks seriously.

Civil society:

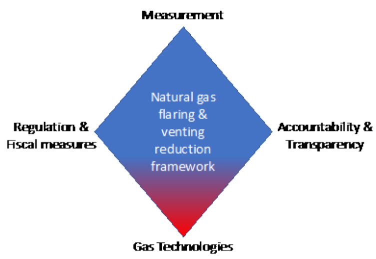
- **Measurement of air quality is often not part of a mandatory measurement scheme.** Clean Air Asia, an international NGO, has worked over 20 years to advocate for better air quality and healthier, more liveable cities in Asia. The aim is to reduce air pollution and GHG emissions in 1,000+ cities in Asia through policies and programmes that cover air quality, transport and industrial emissions, and energy use. Its work has highlighted that 99 per cent (or 463) of 465 cities surveyed (Romsom and McPhail 2020a) have unhealthy levels of air quality (PM2.5 levels above WHO guidelines). In 2016, the OECD and the IEA analysed for the first time how the energy sector can help to address the need for cleaner air while continuing to meet global energy requirements and make progress on other development goals, including human health (IEA 2016).
- **Third-party assessment is important to improve data reliability and performance.** In Russia, WWF Russia has been independently monitoring flaring of associated gas since 2008. Its advocacy and campaign work includes the development in 2014 of an Environmental Rating of 20 oil and gas companies together with CREON Capital, a fund management company. The index is produced in consultation with companies, government, and civil society. WWF considers that environmental rankings can be an important tool for the public monitoring of projects and a stimulus for participating companies to improve environmental performance.
- Another example of an **environmental performance index** for companies is in Nigeria. Stakeholder Democracy Network, a Nigerian NGO focused on the Niger Delta, developed an index in 2018 to compare the performance of 43 oil and gas companies operating in the Niger Delta region. It includes gas flared and oil spills, based on data from environmental monitoring tools used by NOSDRA. These include the Gas Flare Tracker. The index is intended to shine a light on industry emissions across the Niger Delta as a way to engage constructively with oil companies and government on how these can be minimized and bring 'long-running environmental problems in the region to an end' (SDN 2020).

- **Enhancing public access to satellite data for methane emissions.** In the US, the Environmental Defense Fund (EDF) led a five-year study on methane, bringing together more than 100 researchers from 40 institutions and 50 companies to measure methane leaks along the oil and gas supply chain. One finding is that oil and gas methane emissions in the US are 60 per cent higher than official EPA estimates. EDF is now working on launching MethaneSAT, designed to continuously map and measure methane emissions with precision. It will be possible to 'see' emissions where they are difficult to track today. Data from MethaneSAT will be available free to help companies and policy-makers spot problems and identify solutions.

Buyers of LNG: Singapore's Pavilion Energy (Jaganathan 2020) is asking suppliers to commit to jointly developing and implementing a GHG quantification and reporting methodology, covering emissions from the well to the discharge terminal. One of two companies approved to import LNG into Singapore, Pavilion has also urged sellers to outline their carbon mitigation efforts, as it aims to eventually make its purchases carbon neutral. The Oxford Institute for Energy Studies has pointed out that the adoption of such frameworks for GHG emissions means that offset arrangements or carbon payments will need to be made, or other markets sought, for non-certified LNG, or LNG which fails to meet these standards (Stern 2019). LNG projects that have lower overall emissions are likely to be able to sell their cargoes at a higher price than others. Prudent project developers should plan to have their carbon and methane emissions for the entire value chain, up to unloading at the regasification terminal, certified by reputable authorities, and to take note of requirements and standards being imposed elsewhere.

The way forward

Consistent and transparent emissions reporting on climate, environment, and health will enhance oil and gas companies' licence to operate and improve operational efficiency, and can serve as an input to SCAR assessments. There is already some evident progress in this area, but efforts from voluntary initiatives (such as GGFR and ZRF) would need to be complemented by more formalized and mandatory approaches (such as is the intent of the TCFD) to provide the transparency, consistency, granularity, and accountability of reported emissions that investors, buyers, and civil society expect.



5 Flare and vent gas development and monetization technologies

This brings us to the third arm of the Diamond model: the possibilities of mobilizing technologies—some already well known but others new and innovative—to help commercialize and capture the potential gains from reduced flaring and venting.

APG development: key points

- There are many different development technologies to commercialize natural gas.
- These technologies have historically been developed for large-scale applications, that for APG require the aggregation of many flare and vent sites to overcome hurdles of commerciality.
- In addition to technology optimization, the monetization of APG also often requires commercial and regulatory solutions, for example to grant access rights to gas evacuation infrastructure and/or the right to sell the gas.
- Technology development has enabled applications that are much smaller in size, through designs that are scalable and modular, and optimized for applications that are containerized and truck-mounted.
- Smaller-scale applications that are suitable for individual large flares negate the need for gas aggregation across multiple producers, and APG monetization can take place within the commercial bounds of the oil and gas licence.
- While gas flaring is often seen as an early field-life phenomenon (i.e. oil fields are producing oil without gas evacuation infrastructure yet in place), the reality is that excess APG production often occurs in the late stages of oil production when reservoir pressures decline. With infrastructure unable to handle the increased gas throughput, the excess APG is often flared. Gas solutions that are mobile, e.g. containerization at a small scale or FLNG at a larger scale, can be applied to avoid late-life flaring and venting.
- For oil and gas developments that are energy intensive, APG can be processed on site (for example using membrane technologies) and used as fuel or converted into power to support oil field operations.
- Other development options than pipeline exports include CNG applications, mini- and micro-scale LNG and GTL, gas-to-wire, and mini-petrochemical applications.
- The APG monetization options applicable depend primarily on gas rate and distance to market. We have compared indicative application ranges and costs for a number of gas development technologies. It is recommended that the impact of recent technology developments on the commercial viability of small gas projects is updated, so that the economic screening values can be refreshed.

5.1 Successes in flare gas development

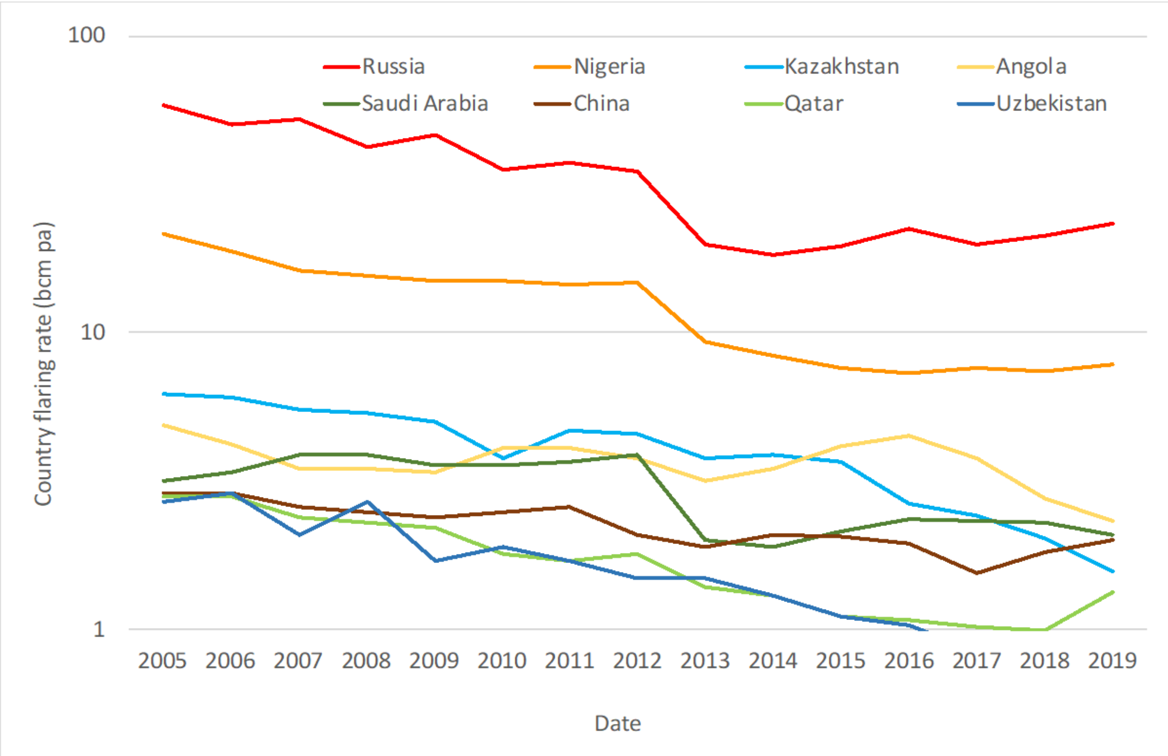
Some countries with historically large volumes of flaring have been able to reduce these emissions, through the development and monetization of APG. In the period 2005–19, Russia was able to reduce flaring the most, followed by Nigeria, Kazakhstan, Angola, Uzbekistan, and Qatar; see Figure 15. The key hurdles that need to be overcome to reduce flaring are invariably oversupply of APG at a place and/or time of low gas demand, competition from other energy sources, lack of infrastructure, and/or other institutional, political, and regulatory impediments.

The general options for gas utilization or monetization are:

- use natural gas for in-field oil and gas operations (reservoir reinjection and/or fuel);
- use natural gas locally, e.g. for domestic purposes, such as heating and cooking;
- use natural gas locally for power generation and industrial use;
- use natural gas locally for transportation, e.g. CNG and LNG;
- export natural gas by pipeline;
- export natural gas by LNG;
- convert natural gas into (export) products with high added value, such as petrochemicals, methanol, fertilizer, dimethyl ether (DME), GTL, etc.

These monetization options complement gas reinjection as a source of strategic gas storage or permanent gas disposal.

Figure 15: Countries that reduced natural gas flaring during the period 2005–19



Note: the y-axis is on logarithmic scale.

Source: authors' illustration based on GGFR global flaring data (multiple annual public releases).

Sometimes, the hurdles for APG monetization come from an unexpected source. In Russia for example, oil companies producing APG compete with gas companies, such as Gazprom, for infrastructure and market access. Oil companies seek a first right for infrastructure access to avoid having to reduce oil production in the case of gas throughput reductions. This limits commercial options for gas producers to optimize their production levels and allocation. When regulations split oil and gas as separate industries, oil producers often find themselves blocked from using existing infrastructure and need to find alternative monetization options for their APG. Part of Russia's success in reducing gas flaring is the result of government intervention to provide priority access to Gazprom's Gas Transportation System for oil companies' APG (see Box A).

Box A. Russia: the challenges for further reductions in natural gas flaring

For decades, Russia has ranked first among the world's largest flaring countries. In 2005, Russia flared 58.6 bcm of gas. According to 2006 data, more than 80 per cent of the total volume of Russian APG was produced by five oil companies—Surgutneftegaz, TNK-BP, Rosneft, LUKOIL, and Gazprom neft. Over a period of nine years to 2014, Russia managed to reduce its gas flaring by 69 per cent to 18.3 bcm through a range of measures and developments.

Natural gas flaring and venting reduction framework

- **Improved measurement.** Gas flaring is not regularly metered in Russia. According to the government of the Khanty-Mansiyskiy Autonomous District (KMAO), which produces more than 50 per cent of Russia's APG, only half of the flares were metered in 2007. However, satellite observations by VNF then identified the true scale of Russia's flaring. Satellites provided comprehensive and regular flaring data, despite the vast expanse of the country, remoteness of its oil and gas fields, and access difficulties (particularly during Siberian winters). In 2006, the Central Dispatch Office of the Russian Fuel and Energy Industry reported country flaring of 14.1 bcm, only 28 per cent of what was recorded by VNF (50.3 bcm). In 2012, the official flare statistics had risen to 17.1 bcm, still only about half of the 34.8 bcm recorded by VNF that year. In 2006, Russia's APG utilization, inferred from its reported gas flaring, was 73 per cent (55 bcm produced, 15 bcm flared, 26 bcm consumed for oil field service needs, including losses, and 14 bcm supplied for processing). However, VNF data measured 50 bcm of gas flared. Production was therefore at least 35 bcm higher (at 90 bcm), implying a utilization rate of only 45 per cent, of which 16 per cent was processed and 55 per cent was flared. This shows that inaccurate flaring data underestimate the opportunity value of natural gas wasted, as well as the degree of environmental, climate, and health damages, while overestimating the efficiency of oil and gas operations.

- **Accountability, transparency, and reporting.** Russia has been working with GGFR, the European Bank for Reconstruction and Development (EBRD), WWF, and other organizations to improve on the accuracy of its gas flaring reporting. This has triggered a number of high-profile initiatives to reduce flaring. However, Russia's representation in GGFR is limited to KMAO, although the Russian state is a declared supporter of the World Bank's 'Zero Routine Flaring by 2030' initiative.

- **Gas development and monetization.** Russia's oil and gas industry is decentralized and fragmented, creating obstacles to APG development. Furthermore, many oil fields are remote from gas infrastructure and markets. Long gas pipelines and gas compression make gas evacuation often uneconomic. APG would need to be aggregated from multiple producers to create economies of scale. Even then, gas companies such as Gazprom have monopolies and see APG from oil companies as competition to their commercial interests. Declining reservoir pressures in older oil fields cause the production of excess gas volumes. During 2000–12 many older oil fields in Siberia were in this reservoir blow-down phase, and they are currently shut in. Mobile LNG technologies currently exist that can capture additional gas volumes from late-life operations. In newer oil fields, the rising petrochemical industry in Russia provides opportunities to develop APG volumes without stepping on the toes of the Russian gas companies. In 2018, Sibur's petrochemical facilities in Western Siberia utilized 22.3 bcm of Russia's APG. Sibur manages the gas aggregation from different operators and operates a network of 2,700 km of pipelines in Western Siberia. Similar opportunities on a smaller scale can be observed across the country. In another initiative, the Blue Line Project Company brought relevant partners together in a public–private partnership to implement several gas flaring reduction projects, such as liquified petroleum gas and gas-to-power plants. This company aims to replicate this experience in other regions in Russia. Due to these initiatives, APG utilization in KMAO increased to 86 per cent in 2011, although 5.4 bcm was still flared.

- **Regulation and fiscal framework.** In 2009, Russia adopted a decree requiring APG utilization of at least 95 per cent from 1 January 2012 onwards. In addition, the Russian central government facilitated higher-priority access for APG producers to Gazprom's Gas Transmission System (GTS). Consequently, at the Vankor oil field complex, the addition of compressor stations and connections to GTS reduced flaring by 77 per cent from 2012 to 2017. Although regulators and district governments have undertaken many initiatives to boost the use of APG, in 2017 19.9 bcm of the 98.3 bcm of APG was still being flared (20 per cent). Under-investment is a key reason for the shortfall from the 95 per cent gas utilization target. Carbon Limits calculated that Russia would need to invest US$8 bn to reach the 95 per cent target for existing production sites and an additional US$16 bn would be needed to meet this target from new production.

Sources

A. Knizhnikov and N. Poussenkova, *Russian Associated Gas Utilization: Problems and Prospects*, Moscow: Institute of World Economy and International Relations of the Russian Academy of Sciences and WWF Russia, 2009.

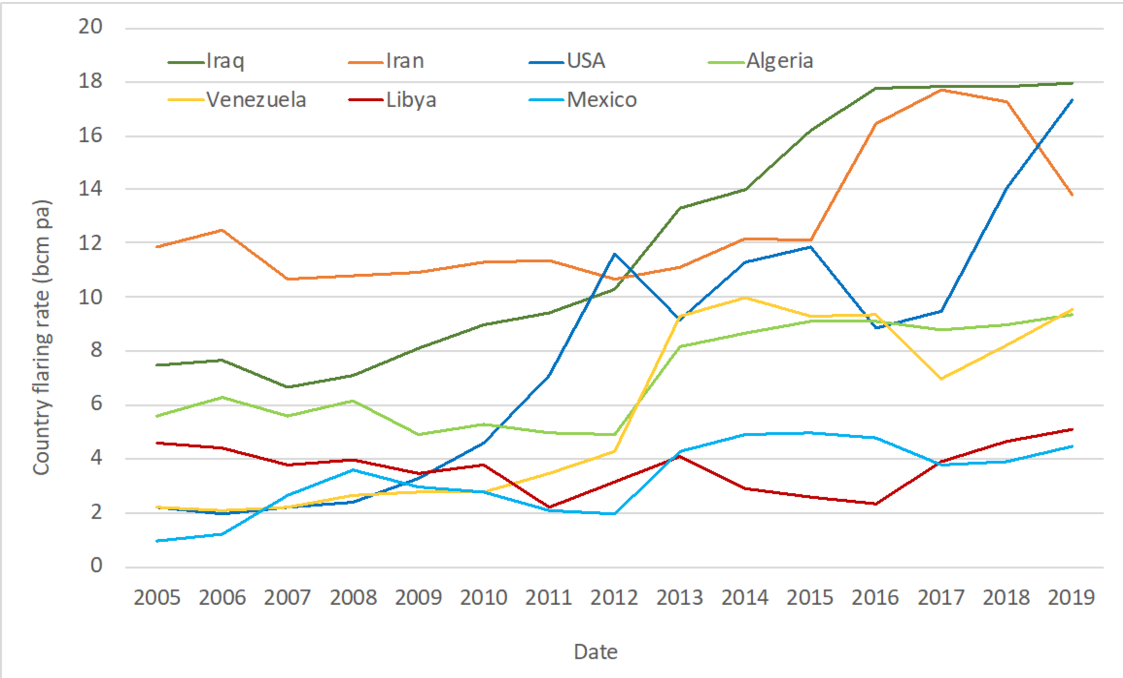
World Bank Group, 'Igniting Solutions to Gas Flaring in Russia', 12 November 2013.

D. Frolovskiy, 'Gas Flaring Remains Issue for Russia', *Asia Times*, 11 December 2019.

Haugland et al., *Associated Petroleum Gas Flaring Study*.

Obstacles to infrastructure availability and access, such as described in Box A, can cause flaring to increase over time. The notion that gas flaring is an early development phenomenon is not always accurate. Many fields exhibit rising APG rates as they become older and reservoir pressures decline. When the oil production in these fields is finally shut in, the flaring also stops. However, for large (clusters of) oil fields that have much life left, large gas aggregation projects to create feedstock for petrochemical plants or LNG export facilities can create commercially attractive developments that also reduce gas flaring. The development of LNG plants in Nigeria, Qatar, and Angola has contributed to reducing gas flaring in these countries. Angola LNG was the first LNG plant to be dedicatedly supplied with APG. APG is the single source of gas production in Kazakhstan. The Kazakh government focuses on strong enforcement of its anti-flaring policies, in combination with the development of domestic gas demand (1.5 Bcfd) and gas export via the Turkmenistan–China Gas Pipeline (1 Bcfd). Gas reinjection to optimise oil recovery further improves gas resource utilization and avoids flaring. High-cost pipeline exports and low domestic prices are made economically viable out of oil profits. In contrast to the above successful examples of flare reduction efforts, several other significant countries show the opposite trend; see Figure 16.

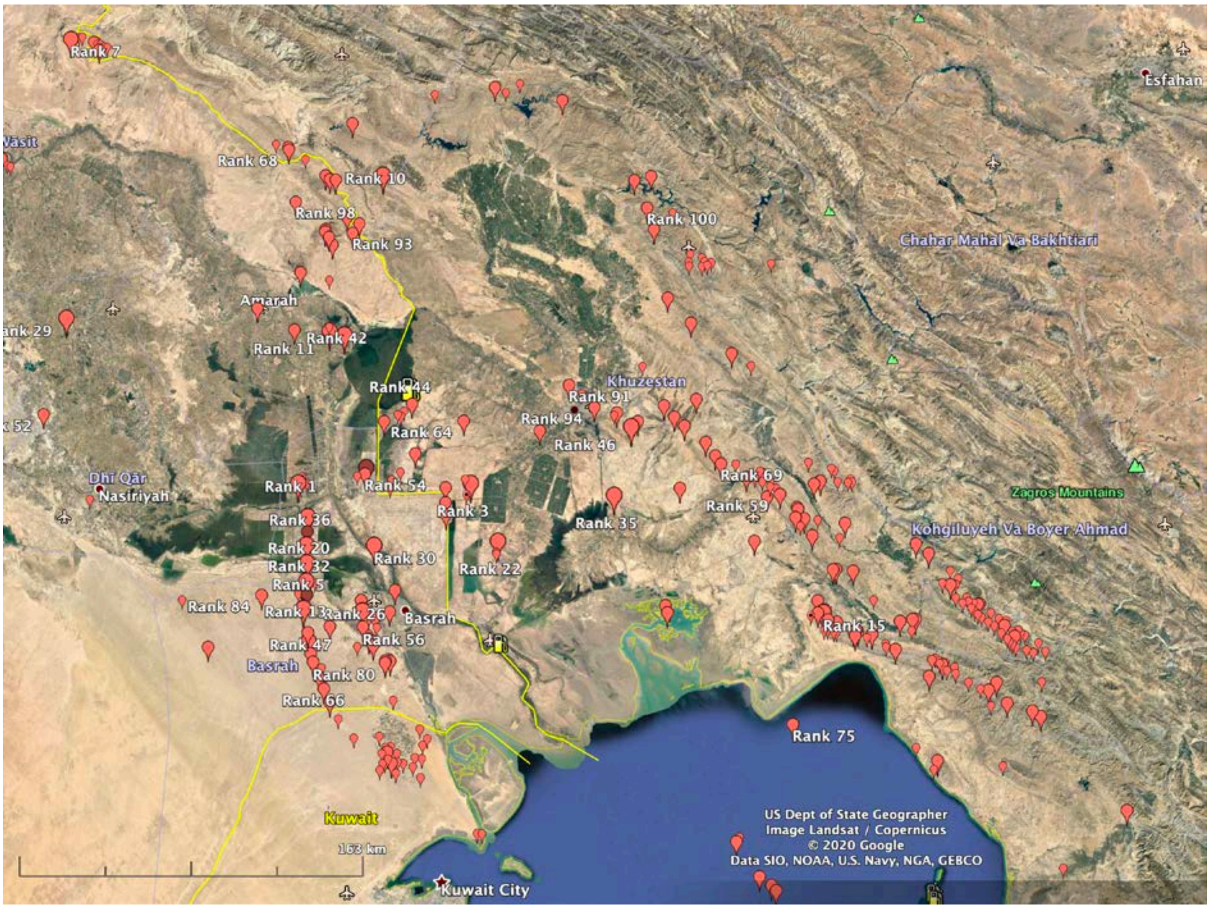
Figure 16: Countries that increased natural gas flaring during the period 2005–19



Source: authors' illustration based on GGFR global flaring data (multiple annual public releases).

Countries with remaining opportunities for large-scale APG monetization projects are Iraq, Iran, and the USA. While Iraq and Iran have many large flares (see Figure 17), the flares in the US are even more abundant, yet they are smaller and distributed among many different oil producers. This increases the technical and commercial complexity of gas aggregation. However, the prevalent gas infrastructure network in the US means that APG can be monetized at that point of access and that it is not necessary to participate in the whole value chain to have the gas monetized.

Figure 17: Abundance of large gas flares in Iraq and Iran



Note: the abundance of large gas flares in Iraq and Iran located near the northern part of the Arabian Gulf makes these prime opportunities for gas aggregation to feed LNG developments. Furthermore, Kuwait currently depends on LNG imports to meet domestic gas demand, while excess gas is flared just across the border in Iraq.

Source: authors' illustration based on a combination of Google Earth images with 2017 VIIRS data.

For most cases where APG is flared, large-scale gas aggregation may not be an option and the only way to monetize the gas is through small-scale gas development. Many gas technologies originally developed for large-scale development have since been further matured and refined for much smaller-scale gas opportunities, such as flared gas.

5.2 Technologies for small-scale commercialization of APG

As described in Section 5.1, there are multiple opportunities to monetize natural gas. In this section, we will describe how recent technology advancements have made previous large-scale gas monetization options now also commercial for small-scale gas opportunities such as APG. Where available, we have included indicative technical costs that have been reported elsewhere. The key challenge of small-scale gas monetization has been to reduce costs through scalable and modular design optimization, and applications that are containerized and truck-mounted. Small-scale gas monetization of APG can also contribute to providing energy access to agricultural and remote communities in developing countries. The small-scale gas monetization options described in this section are then summarized in Table 3 in Section 5.3.

5.2.1 Gas processing

Upstream flare gas is seldom processed before it is flared. The burning of unprocessed gas can cause significant degradation in hydrocarbon destruction efficiency. Good quality flares target a destruction efficiency of 98 per cent.[8] For a flare to function well, it is important to remove fluids in the gas prior to flaring, e.g. with a knock-out drum. Without such equipment, slug flow[9] may cause liquids to enter the flare stack and cause an incomplete burn of the hydrocarbons, significantly increasing the SCAR. If liquids enter the flare stream they can cause sprays of burning chemicals, smoking, and/or extinguishing of the flame. In the latter case, emissions will be no longer flared but vented, which has a much higher SCAR than a well-operated flare.

Whether the objective is to improve the quality of the gas flaring process, to utilize the gas as fuel for oil field operations, or to commercialize the gas, it is important that the gas is processed to a specification that ensures a clean burn. For operations targeting export-quality gas, such processing can involve complex and expensive equipment. However, lower-cost and simplified gas treatment options are available to clean up the gas sufficiently for local use (fuel or power) or for flaring. Gas conditioning membrane units are a commercially attractive processing option. The advantages of using membranes include their passive operation without the use of any moving parts. They are designed to work in unstaffed operations and are practically maintenance-free. Apart from standard filtration, they are designed to work as stand-alone units. When an unprocessed gas flow is led through the membranes, they will filter out heavy hydrocarbons, acid gases, VOCs, and water to provide a clean, combustible natural gas. Large variations in the heat content of the feedgas can be brought in range by adding additional membrane modules in the same unit. Applications range from 0.1 to 110 MMscfd.[10] The above specifications make membranes ideally suited for unprocessed APG, even for single well applications. Membrane equipment is scalable and modular, with containerized and truck-mounted applications for unit sizes up to 5 MMscfd. Costs are in the range of US$7–8 million for 5–7 MMscfd capacity and $10–15 million for 10–15 MMscfd.

An example of a small-scale (0.3 MMscfd) gas processing application, whereby membrane-processed natural gas displaces diesel in a dual-fuelled engine, shows a pay-out period of ten months (based on an investment of $450,000, creating fuel cost benefits of $47,000 per month) (Joshi et al. 2015). The performance data (gas composition) for this application are presented in Addendum A of our first gas flaring paper.

5.2.2 Gas aggregation

Gas aggregation may be necessary to create economies of scale for gas development, particularly when individual flares are too small for stand-alone solutions. Gas aggregation often has many regulatory and commercial hurdles. These include ownership rights to gas resources and infrastructure (pipelines), landownership, permitting issues (right of way; health, safety, security, and environmental impact assessments), the right to sell gas locally and/or to export markets, etc.

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[8] A destruction efficiency of 98% equates to a combustion efficiency, i.e. full conversion into CO_2, of 96.5% (EPA OAQPS 2012).

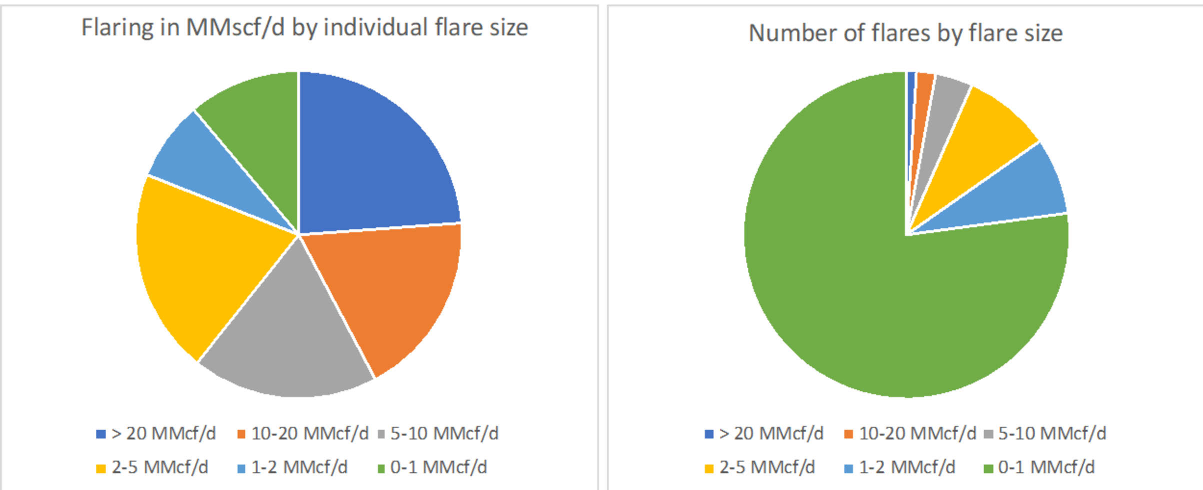
[9] Slug flow is a multiphase-flow regime in pipes in which most of the lighter fluid is contained in large bubbles dispersed within, and pushing along, the heavier fluid.

[10] 100 MMscfd is approximately 1 bcm per year. A single generator in oil field operations typically uses 0.05 MMscfd of fuel gas, while a multi-unit compressor station uses 5 MMscfd.

Apart from commercial complexity, there are also technical issues to consider, particularly when the individual production gas streams are relatively short lived (0.5–5 years). Investments in pipelines, manifolds, metering, etc. can become uneconomic unless these investments have a long period of economic use. One solution that could create improved returns is reusable coiled tubing pipelines (coiled line pipe). The benefit of using this technology is not only the pipelines' applicability for reuse but also their low laying cost. Coiled line pipe sizes exist from ¾-inch to 5-inch outside diameter (OD), with wall thickness typically ranging from 0.087 to 0.337 inches. Such lines can be used as production well flowlines, gas injection lines, and temporary and permanent fuel lines (including natural gas).

Figure 18 shows the size distribution of all global flares identified by VNF in 2017. More than three-quarters of all flares consumed less than 1 MMscfd on average during the year. However, a small fraction (6.6 per cent) of 700 flares consumed more than 5 MMscfd and these are responsible for 61 per cent of all gas flared globally. Depending on their geographical locations, political factors, and other considerations, these large individual flares are prime candidates for the types of gas development and monetization discussed in this section. However, APG volumes from clusters of smaller flares can, when aggregated, also provide a sufficient commercial volume to support development.

Figure 18: A small fraction (6.6%) of all global flares consume 61% of natural gas flared



Source: authors' illustration based on 2017 VIIRS data.

5.2.3 Compressed natural gas

CNG is natural gas pressurized to a range of 100–250 bar, with the aim of increasing its energy density, making the transportation and storage of small natural gas volumes commercial. Until recently, CNG could only be transported to market over land (using trucks) and this restricted its economic viability to volumes of up to around 5 MMscfd and market distances ranging up to 200–800 km.[11] Maximum CNG capacity per truck is in the range of 0.25–0.44 MMscf. However, recent developments now allow CNG to also be transported by maritime carriers. In 2016, a world-first CNG carrier with a tank size of 2,200 m^3 and a CNG carrying capacity of 25 MMscf was launched to supply the island of Lombok in East Indonesia with natural gas for power generation from

[11] The capacity of a CNG facility is not limited by processing size but by commercial issues such as number of CNG trucks required (particularly at longer market distances) and the logistical issues of loading many trucks per day on site.

fields in East Java. In 2019, the American Bureau of Shipping (ABS) approved a design for a much larger CNG carrier that has 200 MMscf of storage capacity (Stenning and Fitzpatrick 2020).

Market applications for CNG have been predominantly focused on its use as an alternative automotive fuel, with the benefit of lowering fuel costs and emissions. In 2019 there were 28.5 million natural gas vehicles (NGVs) worldwide, with the three countries with the largest numbers being China, Iran, and India. Asia Pacific has 20.5 million such vehicles, Latin America 5.5 million, and Europe 2.1 million (NGV Global 2019). Since 2004, the number of NGVs globally has increased at a compound annual growth rate (CAGR) of 14 per cent per year.

In addition to its use as a transportation fuel, CNG is also being used as a gas storage solution, particularly as a backup option for (peaking) power plants. Comparative analysis of CNG and local LNG liquefaction shows that CNG is cost effective for smaller plants and/or lower backup hours. The cost break-even point between CNG and LNG is at approximately 500 MWh per week (i.e. five hours per week for a 100 MW plant, ten hours per week for a 50 MW plant, etc.) (Berg 2018).

In CNG facilities, the main cost component is the storage tank, which needs to be able to withstand high pressures. CNG has the advantage over LNG that different natural gas storage volumes can be accommodated by varying the tank pressure. LNG, meanwhile, is stored at basic atmospheric pressure and the available storage volume is strictly determined by the geometry of the tank.

A separate 2015 study by Tractebel Engineering for World Bank Group and GGFR highlights that CNG transportation costs are the largest cost component, ranging between 79–86 per cent of total cost for long distances (750–1,000 miles) and 57–65 per cent for shorter distances (up to 250 miles). Indicative costs for onshore CNG developments of 3–10 MMscfd in size were estimated at approximately US$2.5/MMBtu + $0.0088 per transportation mile. For a 10 MMscfd offshore development, this cost was estimated at $3.2/MMBtu + $0.005 per nautical mile, while a smaller 3 MMscfd offshore development was estimated at $4/MMBtu + $0.006 per nautical mile (Tractebel Engineering SA 2015).

With a recent increase in cargo capacity, transportation costs for CNG transport by ship are expected to decline and CNG is estimated to be commercial and competitive against other options, such as pipelines and LNG, for delivered volumes of 0.3–7 bcm per annum (30–675 MMscfd) across a transportation distance of 800 km. At 4.7 bcm per year (450 MMscfd), CNG is competitive across a range of 700–2,200 km. At lower levels of production down to 1 bcm (100 MMsfd), CNG is competitive across a distance of 250–1,500 km, and down to 0.3 bcm (30 MMscfd) the economic range is 100–1,000 km (Stenning and Fitzpatrick 2020).

At the low end of the size scale, various technology providers offer modular CNG solutions, such as GE's 'CNG In A Box'™, with unit sizes in the range of 0.2–2.6 MMscfd, scalable up to 20 times for custom-sized CNG packages. This system is modular and each module is transportable by a single truck. Costs are around US$500,000 for a 400 hp CNG system (1.4 MMscfd). This cost excludes power generation requirements (400 kW for a 400 hp system) and the cost of transporting CNG to market.

5.2.4 Mini- and micro-LNG

LNG has a long history dating back to the delivery of the first LNG cargo in 1969. With time, developers have improved the economics of LNG developments through improvements in liquefaction process efficiency and achieving economies of scale by building larger LNG train sizes, up to 7.8 Mtpa (located in Qatar). However, due to market flexibility requirements, smaller liquefaction train sizes of 1–2 Mtpa are becoming increasingly common (Romsom and McPhail 2020b). An LNG train with a size of 1 Mtpa requires approximately 170 MMscfd in feedgas.[12] Large gas flares typically range from 1 to 10 MMscfd, requiring the aggregation of many large flares to feed a single LNG train.[13] Based on LNG project information for the period 2014–18 (Songhurst 2018), costs for LNG plants (outside Australia) generally range from US$600 to $1,100 tpa in capacity, although several factors other than country location can influence the cost (complexity, existing infrastructure, etc.).

However, technology development for mini- and micro-scale LNG has enabled the monetization of significantly smaller natural gas resource volumes, such as flares. In general, LNG is more competitive than CNG for gas rates above around 5 MMscfd. Although providers of mini- and micro-LNG can provide LNG facilities from as low as 8 tpd (0.003 Mtpa, 0.4 MMscfd), typical sizes for commercial mini-LNG plants would be from 5 MMscfd net gas[14] (100 tpd) to 50 MMscfd net gas (1,000 tpd). Designs are modular, which enables scalability. Engineering, procurement, and construction (EPC) costs are approximately US$1.2 million for a 1 MMscfd plant. Annual Opex is approximately 4.5 per cent of Capex (GGFR 2018).

LNG has a growing number of application areas. It can be regasified to regular natural gas and spiked into pipelines and gas distribution grids. It also provides the option of gas storage.[15] It is further used as a transportation fuel in shipping, in locomotives for trains, in heavy-duty high mileage fleets, and in specialized vehicles at airports, mining sites, etc. Particularly with the implementation in 2020 of stricter emission standards by the International Maritime Organization (IMO) in Emission Control Areas (ECAs), the number of LNG-fuelled and LNG-ready ships is expected to grow significantly, and this creates the opportunity for LNG bunkering infrastructure at many waterways and coastal locations.

5.2.5 Gas-to-wire

Many technology providers develop scalable, modular, and truck-mounted generator sets that are containerized, with small-scale capacities using reciprocating engines ranging from 30 kW to 2 MW and larger-scale applications using gas turbines ranging from 250 kW to 30 MW (up to 5 MW per container). Larger-capacity modular units are also possible, ranging from 20 to 500 MW. The gas volume requirement is typically 0.36 MMscfd per MW of capacity. The cost for smaller units (30 kW–1 MW) is typically US$1,000–1,700/kW for systems up to 1 MW and $150–300/kW for multi-MW applications. Many options allow for multi-fuelling, including diesel, propane, and kerosene, in addition to natural gas. Some solutions are designed to handle the variable gas composition (heat content), gas contaminants (including CO_2, N_2, and H_2S), and variable flow rate that are common properties of upstream APG production from oil wells.

[12] One trillion scf feedgas provides sufficient gas to produce 0.8 Mtpa of LNG for 20 years. This equates to 171 MMscfd of feedgas per Mtpa of liquefaction capacity, producing 126 MMscfd of LNG output.

[13] Based on VNF data, the global average flare size is 1.35 MMscfd, while the median flare size is 0.17 MMscfd.

[14] Net gas includes methane and (potentially) ethane only, as other elements such as propanes, butanes and C_5+ liquids, as well as natural gas contaminants, such as CO_2, nitrogen, H_2S, etc. need to be removed from the feedgas before liquefaction. A fraction of the methane and ethane is expected to be utilized as fuel for the liquefaction process.

[15] See Section 5.2.3 for a gas storage comparison between LNG and CNG.

5.2.6 Mini- and micro-GTL

Similarly to LNG, GTL developments have historically targeted large developments for economies of scale. However, mini- and micro-GTL applications have become available to monetize stranded gas. The advantage of GTL production is that the products, such as diesel, are free of contaminants and can be easily stored as liquid fuels. Although units are available as low as 0.2 MMscfd (20 bpd), more likely commercial applications range from 15 MMscfd (1,500 bpd) to 150 MMscfd (15,000 bpd). Also, these GTL technology applications are modular, scalable, and containerized. Some units produce synthetic crude that can be transported for further upgrading to diesel and naphtha, while other technologies produce diesel, wax, and water from unprocessed natural gas feedstock. Typical product yield per MMscf of feedgas is 100 bbl diesel, 1 bbl wax, and 2 bbl clean water. Indicative costs are US$45 million for a 10 MMscfd plant and Opex per annum at 1.2 per cent of Capex, plus the cost for 7 MW of power requirements.

5.2.7 Methanol, ammonia, DME, propylene

Partial oxidation of natural gas produces methanol, ethanol, and formaldehyde as products. A 0.3 MMscfd plant can be installed in a 40-foot container. Unit sizes are available from 0.3 to 10 MMscfd, with potential scale up to 30 MMscfd. The cost for a 0.3 MMscfd unit is US$1,300/tpa capacity, while a 5 MMscfd is $450/tpa capacity. Add-on technologies can be used to produce DME, gasoline, and other high-value products. The amount of feedgas required per ton of methanol is approximately 0.0313 MMscf. Other than feedgas, the application requires power and oxygen that can be generated on site. A 0.3 MMscfd unit therefore produces 3,500 tpa of methanol and a 5 MMscfd unit 58,200 tpa.

Another process option converts APG into propylene. Plant sizes vary from 8 to 150 MMscfd. The EPC cost for a self-sufficient plant is approximately US$200–250 million for 0.08 Mtpa of polymer-grade propylene, with Opex US$220/ton of propylene for a stand-alone self-sufficient plant (excluding the cost of feedgas). The amount of feedgas required per ton of propylene is approximately 0.1 MMscf.[16] A 0.08 Mtpa plant therefore requires a feedgas rate of 22 MMscfd.

5.3 Comparison of monetization options for unprocessed gas

Table 3 provides a summary of the various gas monetization options discussed in the previous sections, comparing scale (in terms of MMscfd) and typical cost factors (in terms of US$ per MMscfd of processing capacity).

[16] Air Liquide's methane-to-propylene (MTP) process uses a chemical conversion of natural gas to methanol, which is then dehydrated using catalysts into DME. The DME is then further converted into propylene; 1 Mtpa of methanol requires a feed of 86 MMscfd natural gas, while 1 Mtpa of propylene requires 275 MMscfd of feedgas; see also Fielden (2015).

Table 3: Summary of monetization options for flare gas

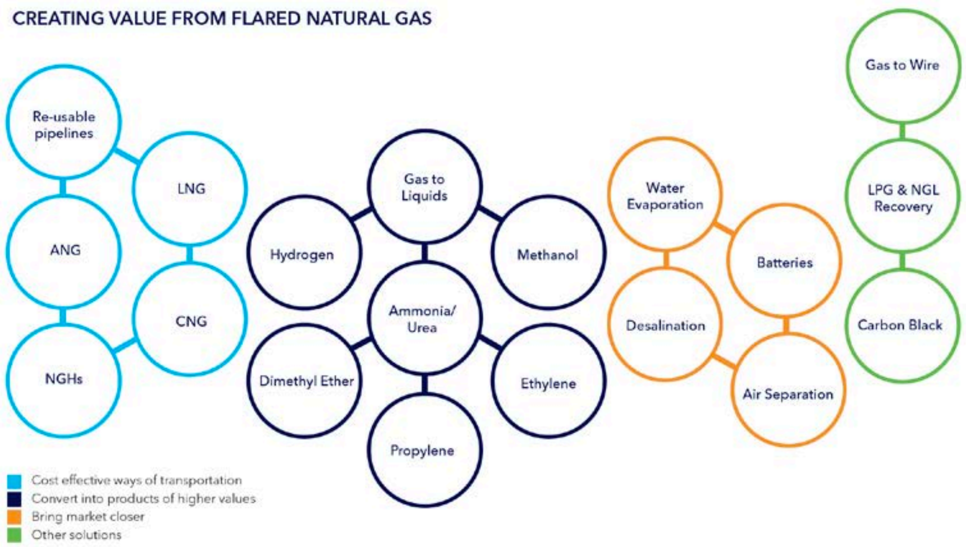
APG monetization Options	Technical size range* (MMscfd)	Typical application range (MMscfd)	Typical cost** (US$ m/MMscfd)	Comments
Gas membrane processing	0.1–110	1–15	1.5 @ 1 MMscfd 1.0 @ 15 MMscfd	To create fuel for local oil and gas services
Gas-to-wire	0.01–180	0.1 @ 30 kW - 11 @ 30 MW	2.8–4.7 @ 0.36 MMscfd 0.4–0.8 @ 3.6 MMscfd	$1,000–1,700/kW $150–300/kW (0.36 MMscfd/MW)
CNG	0.25–15	0.25–5	0.35 0.3–0.5 0.86–1.6 1.5–2.5	CNG in a Box™ + 400 kW power + transport total
			@ 1.4 MMscfd	$2.5/MMBtu + $0.88 per mile
Mini-LNG	0.4–50	5–50	1.2	+ annual Opex at 4.5% of Capex
Mini-GTL	0.2–150	15–150***	4.5 6.5–10	Calvert Energy GTL GasTechno GTL
			0.67–1.13	+ power unit + annual Opex at 1.2% of Capex
Mini-petrochem	0.3–30	2–10	15.1 @ 0.3 MMscfd 5.2 @ 5 MMscfd	Methanol
	8–150	8–150	9.1–11.4 @ 22 MMscfd	Propylene
LNG	170–1,360 per LNG train	170–340 (1–2 Mtpa)	3.5–6.5	$600–1,100/tpa 170 MMscfd/Mtpa

Note: * technical size range indicates the natural gas throughput rate that each technology realistically can accommodate; typical application range is further constrained by commercial considerations. ** This column shows Capex costs per MMscfd of throughput capacity. For example, a 0.5 MMcsfd gas-to-wire power solution is expected to cost US$1.4–2.35 m, while the cost of a 5 MMscfd facility is estimated at $2–4 m. *** A 1 MMscfd GTL plant yields approximately 100 bpd of diesel, 1 bpd of wax, and 2 bpd of clean water.

Sources: authors' construction from own calculations based on GGFR (2018), Songhurst (2018), and Joshi et al. (2015).

In 2015, following the launch of the World Bank's 'Zero Routine Flaring by 2030' initiative, DNV GL conducted a study to compare a variety of gas monetization options for flare gas (Turander 2015). In addition to the technologies mentioned above, DNV GL considered options that were categorized into four solution areas: (1) cost-effective methods of gas transportation, (2) converting gas into products of higher value, (3) options to create local markets, and (4) other solutions; see Figure 19.

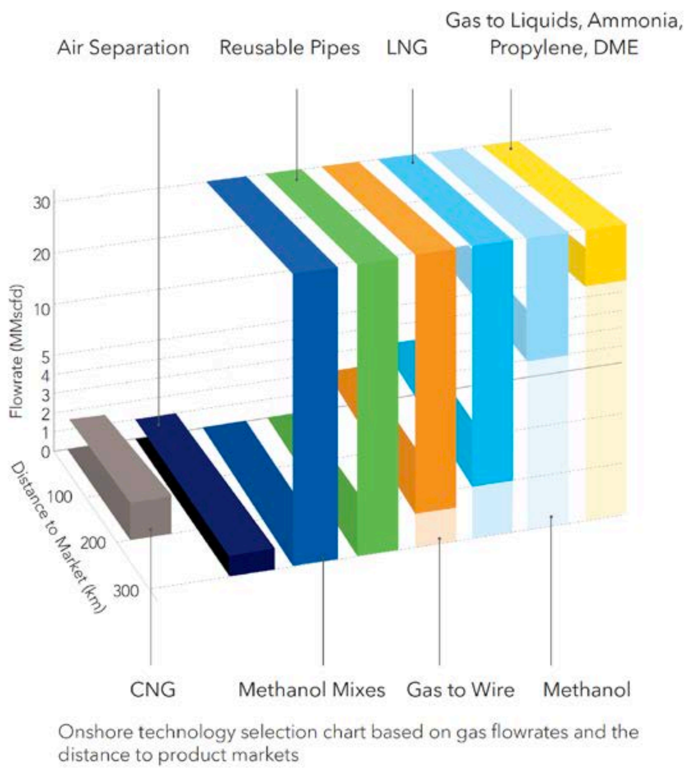
Figure 19: Flared gas monetization options



Source: reproduced with permission from DNV GL (2015).

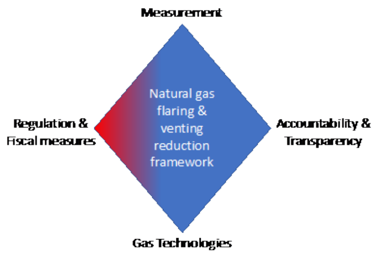
The DNV GL study identified gas rate and distance to market as the two key criteria that determine the choice for commercialization of the various technologies under consideration; see Figure 20. Further technology development, such as micro-LNG, batteries for electrical storage, transportation of CNG by ship, etc., has created some additional new development options and the possibility of reduced cost. The impact of these recent developments on the commercial viability of projects would need to be updated, so that the values in Table 3 can be refreshed.

Figure 20: Screening criteria for flared gas monetization options



Source: reproduced with permission from DNV GL (2015).

In Section 7, we will apply the principles for flow rate and distance to market to conduct a high-level screening of linking gas monetization technologies to market opportunities for specific (clusters of) flares in a sample of 12 countries (see Table 5).



6 Regulation and fiscal measures

The final component of the Diamond model relates to the various regulatory challenges that need to be addressed in order to capitalize fully on the ideas presented above.

6.1 Flaring and venting regulation framework

Regulation: key points

- Regulation is the preferred instrument of the IMF and the World Bank GGFR to 'universally discourage' gas flaring and venting.
- By 2020, the IEA reports ten countries with policies/measures in place for climate change, as well as for flaring and methane. However, the countries included by the IEA differ from those in the GGFR review of upstream flaring and venting regulation.

Flaring

- IEA data show that about a third of the top 30 global gas flaring countries have flaring regulations in place.
- Results are mixed in terms of whether countries with regulation are successful in reducing the volume of flared emissions. Between 2005 and 2019, Russia, Nigeria, Indonesia, and Colombia reduced flare volumes. Canada, Brazil, and Australia maintained stable volumes, some with increased oil production. Since 2017, Mexico and the US significantly increased their volumes of gas flared.
- Eight of the ten countries with flaring regulations are among the top 30 countries for flaring volumes.
- Regulations typically focus on limiting volumes. Flare quality is even more important. The social cost of flaring increases immensely when the quality of the flaring process does not meet its 98 per cent destruction efficiency target.
- Regulators should require oil and gas companies to also measure flare quality (i.e. chemical composition of the emissions) to demonstrate and improve their operational performance and minimize their negative environmental impact (SCAR).
- Regulation on flaring should coincide with regulation on methane emissions (venting), to avoid causing oil and gas producers to preferentially vent instead of flaring, resulting in an even higher SCAR.

Methane and other non-CO_2 emissions

- Methane is a primary constituent of natural gas and is also a valuable product.
- The IEA reports that the presence of regulations for deliberate venting and leaks of methane have increased since 2015: 13 countries now have methane policies. Mandatory reporting of methane is required in seven countries. The IEA and UNPRI confirm the need for more effective methane regulations in many key regions.
- Methane and other non-CO_2 releases contribute 96 per cent of the SCAR from flaring and venting and at least 52 per cent of the total SCAR of all natural gas, including utilization.

Since 2002, the World Bank GGFR and the IMF[17] have supported voluntary efforts to discourage gas flaring through regulation. However, global public–private voluntary initiatives to reduce hydrocarbon flaring and venting have yet to realize their promise. There was some reduction in gas flaring between 2004 and 2014, yet methane emissions increased over the period. Regulation is generally seen as a key instrument to reduce/ban flaring and venting. Effective regulations may include penalties, with the recommendation that they are sufficiently high to increase the attractiveness of flare and vent reduction investments. The GGFR also points to the importance of a strong and empowered regulatory body, independent from operators, which can establish flare measurement and reporting requirements for operators. Independent regulators also require the resources and authority to monitor flare measurement equipment and flare and vent volumes. GGFR undertook reviews and analytical work on a range of topics, including definitions, approvals, measurement, reporting, monitoring, enforcement, public disclosure of flare and vent data, and third-party access to infrastructure. Partner companies committed to a voluntary global standard to stop existing gas flaring, and to avoid it altogether for new developments.

A first review by GGFR of upstream oil and gas policies for associated gas flaring and venting was undertaken in 2004 and covered 44 countries (World Bank 2004). It found that 'only 18 have set overall emission targets, and only 3 (Alberta Canada, Nigeria and Peru) have developed policy guidelines and/or specific emission targets for gas flaring and venting'. In 2012, GGFR reported that 'Regulations on gas flaring were passed in Russia, Angola, Kazakhstan, Gabon, Cameroon and under development in Indonesia, Nigeria, Qatar, Iraq' (GGFR 2013, see also Section 4).

A comprehensive IMF study (Daniel et al. 2010) on the taxation of EI in 2010 noted that gas flaring is universally discouraged and should be dealt with via regulation. This was reiterated in a World Bank publication (Huurdeman and Rozhkova 2019) which stated that '[n]atural 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.'

The IEA established a comprehensive, online Policies and Measures Database, which by 2020 included 5,000+ past, existing, or planned government policies and measures to reduce GHG emissions, improve energy efficiency, and support renewables (IEA undated).[18] Policies and measures for climate change date back to 1990 and exist in 40 countries (see Table 4 and Appendix B); ten countries have policies on gas flaring and 13 have methane measures, with the latter noticeably increased since the Paris Climate Agreement was signed in 2015.

There are countries in the GGFR database which are not included in the IEA database and vice versa. Given that regulation is the preferred instrument to tackle upstream hydrocarbon flaring and venting, this indicates the need for a more consistent global data source on country flaring

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[17] The IMF was active starting in 2011 in capacity-building for (the increasing number of) low- and lower-middle income countries dependent on mining and petroleum activities. Through a dedicated trust fund, priority was given to the design and implementation of the extractive industry fiscal regime; revenue administration; macro-fiscal and public financial management; natural resource funds; and statistics. This was followed by a second fund, 2017–22. One objective is to improve potential revenue flows to host governments over project life cycles, while providing predictability and stability to extractive industries (EI) companies and preserving attractive returns to investment and production (IMF 2017).

[18] This unique policy database (https://www.iea.org/policies) assembles data from the IEA/IRENA Renewable Energy Policies and Measures Database, the IEA Energy Efficiency Database, the Addressing Climate Change database, and the Building Energy Efficiency Policies (BEEP) database, with information on carbon capture, utilization, and storage (CCUS) and methane abatement policies.

and venting regulations. Best practice regulations (i.e. specific, enforceable, and practicable) are to be identified for lateral learning.

Table 4: Countries and number of policies on climate change, methane, and flaring in July 2020

	Country/region	2019 global flare volume ranking	Climate change policies	Methane policies	Flaring policies
1	Canada	26	28	32	15
2	Australia	20	13	27	7
3	Nigeria	7	0	16	12
4	US	3	7	15	7
5	Mexico	9	3	15	5
6	Norway		9	8	5
7	Indonesia	16	0	4	2
8	Russian Federation	1	0	4	1
9	Colombia		0	4	1
10	Brazil	24	2	2	3
11	Argentina	28	0	4	
12	Turkmenistan	21	0	4	
13	Kazakhstan	18	0	1	
14	EU		16		
15	UK	25	12		
16	France		10		
17	Netherlands		7		
	Total		156	136	58

Source: authors' construction from own calculations based on IEA (undated), 'Policies Database'.

6.1.1 Flaring

Although priority has been given to the importance of regulation as a way to reduce flaring and venting, by 2020 only about 30 per cent of the top 30 global gas flaring countries have adopted regulations, according to the IEA database.

Results are mixed in terms of whether countries with flaring regulations (there are ten of these) perform better in terms of reduced flaring emissions. Eight of these ten countries are among the top 30 countries for flaring volume. Norway is an example of a low flaring country with successful regulations (see Box C). Between 2005 and 2019, Russia (Box A) and Nigeria (Box D) have significantly reduced flare volumes (see also Figure 15). Canada, Indonesia, Brazil, and Australia have stable volumes while Mexico and the US (Box B) have seen a significant increase in CO_2 emissions (Figure 16). The reasons for this very mixed performance are that regulations may not be sufficiently specific, are difficult to enforce by the regulator, and may be impracticable to implement for the oil and gas industry.

Box B. USA: regulation, comprehensive reporting of individual atmospheric releases, and technology innovation

In 2019, the US was the world's largest oil producer, with a significant onshore (mostly shale development) and offshore industry. The latter is tightly regulated by the federal Bureau of Safety and Environmental Enforcement (BSEE). Until 2005, onshore production took place in a handful of US states. From 2005 the onshore extraction process became decentralized, and it now involves tens of thousands of separate well sites scattered across dozens of local jurisdictions in 32 states. In the US, private ownership of subsurface mineral rights facilitates rapid development of such resources, whereas in most other countries these rights are state-owned. The US ranks in the top three countries by flaring volume in 2019. In our work, we found that 2017 flaring (1.1 per cent) and venting (2.1 per cent) caused by US upstream oil and gas industry caused a SCAR of $26.0 bn (29.4 per cent) and $62.4 bn (70.6 per cent), respectively. In 2019 US flaring had further increased from 9.5 bcm pa to 17.3 bcm per year.

Natural gas flaring and venting reduction framework

The US has separate and distinct regimes for regulating development of onshore and offshore oil and gas resources.

Offshore

- **Improved measurement:** Regulations pertaining to flaring and venting on the US Outer Continental Shelf (OCS) are controlled through the Department of the Interior's BSEE. The BSEE has very restrictive gas flaring policies in order to minimize emissions from flaring and venting. Offshore facilities processing more than 2,000 bpd of oil on average must install flare or vent meters with about 5 per cent accuracy. Operators must keep detailed flaring records, which are subject to inspection. Flared gas volumes must be reported as a part of monthly production statements. In 2017, there were 41 offshore flares out of a total of 3,686 US flares.

- **Regulation and fiscal framework:** Offshore mineral resources (Alaska, Gulf of Mexico, and Pacific) are owned by the US government and are managed by the Bureau of Ocean Energy Management. Offshore operators must request and receive approval from the BSEE regional supervisor to flare or vent natural gas, except in situations that include operational testing, emergencies, and equipment failures. BSEE Notices to Lessees (NTL) 2012-N03 and 2012-N04 provide guidance for requesting approval to flare or vent natural gas. Flaring or venting is permitted on a case-by-case basis at BSEE's discretion on a limited basis. BSEE does not consider the avoidance of lost revenue to be a justifiable reason for venting or flaring. Operators are subject to a variety of federal taxes, royalties, income tax, signature bonus, etc. State taxation laws do not apply to the outer continental shelf.

- **Accountability, transparency, and reporting:** The EPA National Emissions Inventory (NEI) provides a comprehensive database with estimates of annual air pollutant emissions at national, state (including federal waters), or county level, by sector (including oil and gas production, petroleum refineries) and by pollutant category (10 critical air pollutants/CAPs, 3 GHGs, 187 hazardous air pollutants/HAPs). This database provides a valuable resource for SCAR assessments by providing detailed amounts of individual chemical releases.

- **Small-scale gas development and monetization:** Operators must either market produced gas to a pipeline company or transport the gas to shore for sale, use the gas for power generation, or reinject gas to enhance oil recovery. Gas must be produced for sale after the oil production objectives have been achieved (reservoir blow-down). The Gulf of Mexico has a well-established pipeline infrastructure.

Onshore

Onshore mineral interests can be held by (1) the federal government (managed by the Department of the Interior's Bureau of Land Management/BLM and the Department of Agriculture's US Forest Service), (2) states, (3) Indian reservations (managed by the Bureau of Indian Affairs and the BLM), (4) individuals, (5) corporations, and (6) trusts.

- **Improved measurement:** The BLM (see below) designs regulatory reporting requirements on gas flaring and venting, largely for resource conservation. In 2018, the EPA announced that it no longer requires companies to report according to the BLM Venting and Flaring Rule, introduced in 2017, on methane leaked, vented, or flared for oil and gas wells in federal lands. If implemented, this would have required operators to install emissions control equipment on wells, even where it was not economical to do so. Companies are also no longer required to report on other components of the natural gas stream.

- **Regulation:** Both federal and state governments see regulations as more important than carbon pricing to address GHG emissions. Several entities regulate onshore oil and gas operations:

1. **BLM—**part of the Department of the Interior, the BLM regulates siting, drilling, and production activities on federal lands.
2. **The EPA**—the EPA regulates releases of HAPs and other non-methane VOCs from oil and gas production operations. The Clean Air Act requires the EPA to establish federal emission standards for significant sources of air pollution. The aim is to promote use of the best air pollution control technologies, taking into account the cost of such technology, energy requirements, and any non-air quality, health, and environmental impact.
3. **Individual states**—in addition to federal air quality regulations, many of the 32 producing states have their own rules and standards which apply to private lands where mineral rights reside. Some states, such as Alaska, also have reporting requirements (similar to BLM) for venting and flaring.

- **Fiscal framework:** At the **federal** level, no carbon tax is applied, while regional carbon cap-and-trade programmes have often not been sustained. Almost all energy-producing **states** levy a tax on oil, natural gas, and coal. This is done by 'severance taxes',[19] to capture public value from the permanent loss of a natural resource. Methane is generally exempt through methane release exceptions.[20] The IMF finds that shale gas extraction does not warrant a significantly different fiscal regime than that recommended for conventional gas. However, due to the fragmentation of operations in shale basins, regulators should not only manage and limit atmospheric releases per well pad but also restrict such releases in aggregate across the basin. An analysis of the importance of severance taxes to state budgets was undertaken by Rabe and Hampton in 2015. In 2013, eight states obtained 10 per cent or more of total revenues from severance taxes, ranging from 78 per cent (Alaska) and 46 per cent (North Dakota) down to 14 per cent (New Mexico) and 9 per cent (Texas). Severance taxes only cover methane captured for profit, not methane released into the atmosphere. This similarly applies to royalties for **private landowners** who authorize drilling on their property. If methane is captured and used commercially, the producer pays royalties to property owners and severance tax to the state government.
- **Accountability, transparency, and reporting:** A 2019 Report by the Department of Energy (DOE) focuses on upstream hydrocarbon flaring and venting for commercial reasons, given the flaring of relatively large volumes of gas associated with oil production. In 2017, the volume of gas flared and vented reported to the DOE by Texas (101 Bcf) and North Dakota (88.5 Bcf) was 10–20 times higher than that of other states. NGOs, such as Inside Climate News, Institute for Policy Integrity, Environmental Defense Fund (EDF), Environmental Integrity Project (EIP), etc., are increasingly influential in holding regulators to account on their performance, as illustrated in EIP's lawsuit to force the EPA to update emission factors for flares and make these consistent with actual flare emissions (four times higher than previously assumed).
- **Small-scale gas development and monetization:** Routine flaring (i.e. 'flare to produce') occurs in the US predominantly for commercial reasons. Therefore, regulation and fiscal policies are a key instrument to restrict and disincentivize flaring and venting. However, in addition to regulatory measures, technical opportunities for gas capture and development need to be generated to allow APG to be monetized instead of wasted. The 2019 DOE report concludes that the lack of direct market access for APG is the most prevalent reason for ongoing flaring, and points to planned increases in gas processing and pipeline capacity in both Texas and North Dakota. However, integrated development planning and regulatory oversight should have enabled gas evacuation projects to be on-stream simultaneously with the commencement of oil production (and APG) from these basins. As the US has many small flares, smart technologies for gas aggregation are important to create economies of scale. The US gas market is sufficiently developed that gas can be monetized at the inlets of gas transportation pipelines. Moreover, onshore shale development activities are energy intensive, and processed APG should play an increasing role in providing fuel and power to oil and gas field operations.

Conclusion

The US regulations on flaring and venting differ markedly between offshore (federal regulations under BSEE) and onshore developments (subject to multiple state and federal regulations and regulators). The offshore regime under

[19] Severance taxes impose a cost on the extraction of natural resources as they are being severed from beneath the surface of the earth.

[20] Two state legislatures have sought to apply these taxes to methane releases since 2000. Industry opposition, rather than technical feasibility, was the primary factor leading to the rejection of these bills.

BSEE demonstrates that flaring can be successfully managed and constrained. However, the combination of diverse interests of states (including the need for local oil and gas investments), diversity in regulations and regulators, and generally a more relaxed attitude towards onshore regulations compared with offshore has resulted in a much more tolerant approach to issuing flaring permits and enforcing controls on emissions.

Sources

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Satellite data of hydrocarbon flaring, first developed by GGFR and NOAA, allows measurement of individual flares by their size and exact location. This levels the playing field for regulators, as there is no longer a need to rely on companies to self-report. Satellite data provide regulators and governments with access to information on how much natural gas in their country is emitted and lost. This can be used to determine the basis for assessing compliance with emission volume regulations, tax, and/or fines.

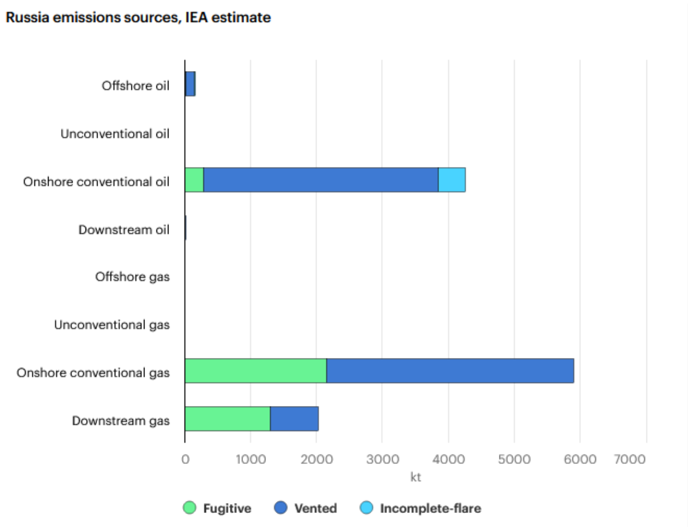
Most regulations focus on limiting volumes. As set out in our earlier paper (Romsom and McPhail 2021, section 2), flare quality is equally important. For flaring, SCAR is distributed across a variety of chemicals, particularly CO_2, BC, SO_2, and NO_X. For venting, methane and VOC emissions account for a 90 per cent and 10 per cent SCAR contribution, respectively. These impacts point to the importance of regulators taking an 'all-of-government' approach in developing regulations, e.g. including ministries of health and financial regulators. The estimated social cost per volume flared is 12.6 times higher than under perfect combustion. 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. due to poor design and/or operations. Poor flare operations negate most of the benefits that flaring has over venting (SCAR for venting is 16 times higher than 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. Regulators should require oil and gas companies to also measure flare quality (i.e. chemical composition of the emissions) to demonstrate and improve their operational performance and minimize their negative environmental impact (SCAR). The knowledge of the oil and gas industry is valuable in providing input into how these regulations can best be implemented.

There can be unintended consequences of anti-flaring policies (Calel and Mahdavi 2020). Even outright flaring bans, such as in Algeria in 2005[21] and Ghana in 2010, have not been followed by reductions in flaring. Focusing only on regulatory reforms to decrease flaring may drive operators to vent instead. Unlike methane, flares are highly visible both to the naked eye and to remote sensing instruments, allowing low-cost identification of point sources and estimation of volumes released. However, technologies for remote methane detection and volume measurement are rapidly improving and various new methane-detecting satellites are planned to be launched in the near future (see Sections 3.4 and 7).

6.1.2 Methane and other non-CO_2 emissions

Methane is the prime constituent of natural gas. Methane and other non-CO_2 releases contribute 96 per cent of the SCAR from flaring and venting and at least 52 per cent of the total SCAR of oil and gas operations, including the utilization of all globally produced natural gas. Regulations have accelerated and there are now 13 countries where these are applicable. Mandatory reporting of methane is also required in half of these countries, including Canada,[22] Nigeria, and the US, although this usually does not cover methane 'leaks', which can be significant (see Figure 21) (Nasralla 2020).

Figure 21: In 2019, Russia's methane emissions were 12.36 million tonnes, representing 15.2% of global methane emissions



Source: reproduced from IEA (2020a), 'Methane Tracker 2020, Interactive country and regional estimates'.

Both the IEA and the UNPRI find that there is a need for more effective regulations on methane. The latter views North America as leading on methane regulations. In 2018, the Pan-Canadian Framework set national goals to reduce methane emissions in Canada, Mexico, and the US. This was followed up in Canada with regulations at federal and state level to achieve the national commitment to reduce methane emissions from the oil and gas sector to 40–45 per cent below 2012 levels by 2025. Action in the US is focused more at the state level, starting with Colorado in

[21] In Algeria there is a strong legal framework on flaring and flaring fines are high, but in 2011 GGFR noted that there was little evidence of monitoring, reporting, and tax collection, which may be in part due to the political power of Sonatrach (CLN 2019).

[22] The Environmental Defense Fund has analysed best practices in three Canadian provinces and at the federal level (EDF undated).

2014. In its 2017 review of global methane regulations, the UNPRI found that other key regions lack effective regulation, including Russia, Nigeria, and Iraq. Since then, Nigeria has published eight new policies and guidelines for methane. In January 2020, together with Côte d'Ivoire, Nigeria joined the Global Methane Alliance (CCAC Secretariat 2020b; UN Environment 2019). The UNPRI concludes that the onus is on large IOCs to limit emissions by implementing international best practice standards together with their joint venture partners and state-owned companies. Some references raise the valid issue that 'good oil field practice' is too vague to drive improved performance. This suggests that regulatory measures for flaring and venting require complementary actions in the areas of measurement, accountability and transparency, and gas monetization, as proposed by our 'Diamond' model.

Norway is one of the few countries that have implemented regulations and fiscal frameworks for individual atmospheric releases such as CO_2, methane, and NO_X (see Box C). These measures have not only reduced emission intensity and improved energy efficiency but have also been a critical driver for technology innovation. However, not many countries have followed Norway's lead to date.

Box C. Norway: combining measurement, regulatory and fiscal frameworks, incentivised industry to develop technologies for small-scale gas development and monetization: all key to the country's low fugitive emissions.

In 2014, Norway ranked 15th among global oil producers, with 85 Mtoe per annum. The country is also the world's third-largest exporter of natural gas (122 bcm in 2017), supplying 25 per cent of the EU's gas demand, mostly by pipeline. Since 2007, there has also been a 4.5 Mtpa Snøhvit LNG plant near Hammerfest, in northern Norway. With large undeveloped gas resources in the Barents Sea, the LNG capacity in Hammerfest has the prospect of significant capacity expansions. Norway's fugitive emissions were 1 $MtCO_2e$ (vs total global emissions of 2,623 $MtCO_2e$) in 2014. From the start of oil production in 1970, the government's policy prohibited routine natural gas flaring to avoid wasting valuable energy. Fiscal policies followed in 1991, with a carbon tax payable by operators for all petroleum operations generating CO_2 emissions, including oil fields. It is one of the few countries to also tax non-CO_2 emissions.

Natural gas flaring and venting reduction framework

- **Improved measurement.** Before an operator can develop a discovery, the Petroleum Act requires that a development plan for the associated gas must be approved by the regulators. The Norwegian Petroleum Directorate (NPD) monitors and strictly enforces flaring prohibitions. Since 1993, oil and gas operators in Norway have been required to meter any flared gas. For venting, there are detailed guidelines on how companies are to measure and report methane emissions.
- **Accountability, transparency, and reporting.** Emissions from the petroleum sector in Norway are well documented. The industry Norwegian Oil and Gas Association (NOROG) has established a national database for reporting all releases from the industry, called the EPIM Environment Hub (EEH). All operators on the Norwegian continental shelf report data on emissions to air and discharges to the sea directly in the EEH. Each year, the NPD compiles historical emissions data and prepares forecasts for activities including gas flaring and venting.
- **Small-scale gas development and monetization.** Almost all of Norway's gas production is exported. This is helped by Norway's proximity to large neighbouring markets for natural gas combined with an existing gas pipeline transportation infrastructure that can access those markets. The incremental cost of investment to monetize APG is thus smaller than for many countries. Norway is also a leading country in the development of small-scale LNG. It has a number of existing small LNG liquefaction plants, such as Risavika (0.3 Mtpa), Kollsnes 1 and 2 (0.04 and 0.08 Mtpa), and Snurrevarden (0.02 Mtpa). One key application of small-scale LNG is transport. A large fraction of the global LNG-fuelled ships are located in Norway, including ferries, tugboats, tankers, and offshore service vessels.
- **Regulation and fiscal framework.** Norway prohibits most forms of flaring and imposes steep fines on methane releases. Emissions from Norwegian petroleum activities are regulated through several acts, including the Petroleum Act, the CO_2 Tax Act on Petroleum Activities, the Sales Tax Act, the Greenhouse Gas Emission Trading Act, and the Pollution Control Act. Norway was one of the first countries to introduce a carbon tax, in 1991. In addition to covering petroleum operations generating CO_2 emissions, it also covers natural gas that is emitted directly into the atmosphere. The effective tax rate is comparable

to the rate that applies to CO_2 emissions from natural gas combustion. This has led to a well-documented methane capture rate that is routinely above 99.8 per cent. Carbon tax rates on oil production increased again in 2014, which further incentivized companies by making flaring reductions lucrative, causing companies to invest in new technologies. The carbon tax which applies to the six GHG emissions in the Kyoto Protocol[23] is classified as a deductible operating cost for income tax purposes in the oil and gas sector, so the net amount of tax is lower than its gross amount. In 2020, the Norwegian carbon tax rate was raised from US$49/t$CO_2$e to $53/t$CO_2$e. As per the protocol to combat acidification, eutrophication, and ground ozone, ratified in Gothenburg in 1999, Norway aims to reduce NO_X emissions by 30 per cent against its 1990 baseline level. To achieve this reduction, a NO_X emissions tax (approximately $2.60/kilo of emissions) has been applied since 1997 at power plants, engines, boilers, turbines, and flares on land and at sea. This measure not only further penalises flaring but also stimulates fuel-switching to natural gas (in particular LNG as transportation fuel).

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6.1.3 Conclusions

- Global public–private voluntary initiatives to reduce hydrocarbon flaring and venting have yet to realize their promise. There was some reduction in gas flaring between 2004 and 2014; methane emissions increased over the period. As a consequence, regulation has generally been seen as a key instrument to reduce/ban flaring and venting. However, more work is needed to establish a consistent global data base by country on effective regulations for flaring and venting.
- Only a few countries appear to have specific regulations for flaring and/or methane emissions. Furthermore, the impact of these regulations is mixed among those countries. Some countries have been very successful in curbing emissions, others less so. More work is needed to assess how venting and flaring regulations can be made more effective.
- Regulations need to be sufficiently specific, enforceable by the regulator, and implementation practicable for the oil and gas industry. The knowledge of the oil and gas industry is valuable in providing input into how regulations can best be implemented. Best practice regulations are to be identified for lateral learning.
- For flaring, SCAR is distributed across a variety of chemicals, particularly CO_2, BC, SO_2, and NO_X. For venting, methane and VOC emissions account for a 90 per cent and a 10 per cent SCAR contribution, respectively. These impacts point to the importance of regulators taking an 'all-of-government' approach in developing regulations, e.g. including ministries of health and financial regulators.
- The social cost of flaring increases significantly when the quality of the flaring process does not meet its 98 per cent destruction efficiency target. Regulators may require oil and

[23] The six greenhouse gases currently covered by the UNFCCC/Kyoto Protocol are: CO_2, methane (CH_4), nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6), and nitrogen triflouride (NF_3), see also UNFCCC (undated).

gas companies to also measure flare quality (i.e. chemical composition of emissions) to demonstrate and improve their operational performance and minimize their negative environmental impact (SCAR). Regulatory focus should be directed to super-emitter flares (and vents).

6.2 Flaring and venting fiscal framework

Fiscal policy: key points

- The 2015 Paris Climate Agreement signed by 190 countries aims to keep future global warming below 2° C. Countries' voluntary nationally determined contributions (NDCs) are not sufficient to achieve this goal. The IMF and others consider that carbon taxation is the most effective instrument to achieve the Paris targets on the basis that taxing all fossil fuel CO_2 emissions provides across-the-board incentives for energy efficiency and transition to cleaner fuels.

CO_2 taxation

- As of 2020, there are carbon pricing schemes in 46 countries and 32 cities, states, and provinces. These cover only 20 per cent of global emissions and are deemed 'inadequate'. The average global carbon price is US$2/$tCO_2$. Ideally, carbon tax should be set equal to the social cost of carbon. The IMF recommends that a much higher range is required ($40–80/$tCO_2$) to achieve 2° C or less.
- However, the contribution of CO_2 to the SCAR from flaring is less than 10 per cent, as the greatest flare SCAR contributions are from NO_X, SO_X, and BC.
- Therefore, fiscal measures for flaring should focus primarily on the quality of flaring. If flare combustion quality rises, so do CO_2 emissions at the expense of a reduction in more damaging chemicals.
- In addition, taxation of CO_2 emissions from flaring will further disincentivize waste of APG as a natural resource, as well as benefiting action against climate change.

Methane and other non-CO_2 emissions taxes

- Few countries tax methane and other non-CO_2 emissions. If they do so, it is usually on the basis of CO_2e, which does not capture the full SCAR of methane.
- The IMF recommends an emissions tax for methane based on a default leakage rate, with rebates to companies that demonstrate, via continuous monitoring, lower leakage rates. This can be extended to each of the other atmospheric emissions.
- Special fiscal treatment can help companies with up-front capital costs and (relatively) lower rates of return for APG capture and monetization compared with oil production. Governments may also provide tax credits for imports of certain technologies and equipment that could make gas monetization investments commercial, when such equipment cannot be fabricated locally.

Additional benefits include:

- Given the global scale of hydrocarbon flaring and venting, considerable economic value is forgone: if 75 per cent of global upstream gas could be captured and brought to market, it would provide US$36 bn of additional annual sales (at an average gas price of $4/MMBtu). The monetization of APG can help to provide energy access for the more than 1 bn people who currently have no access to electricity and the 2.8 bn people who do not have access to clean cooking fuel (SDG7).

There is broad agreement that, wherever possible, governments and regulators should price in the cost of externalities. This approach is supported by most leaders in the energy sector, the global investment community, and others, who have called for 'economically meaningful carbon pricing regimes, whether based on tax, trading mechanisms or other market-based measures' to be set at a 'level that incentivises business and consumer behaviour to accelerate the energy transition' (Total 2019). However, there are many practical difficulties in implementing such an approach. Our previous WIDER Working Paper demonstrates the scale of the challenge: 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 (Romsom and

McPhail 2021). The paper also demonstrated that flaring and venting emit a range of different chemicals, each with different SCAR impact, not only climate-related but also affecting air quality, health, toxicity, and precipitation. Therefore, fiscal measures need to be practical yet account for the different chemicals and their different impacts. Climate-driven measures in isolation risk neglecting non-climate risks and facilitating compensating measures (e.g. purchase of CO_2 certificates) that do not address other emission impacts (e.g. health) or the wastage of valuable APG resources.

6.2.1 Flaring

Almost 190 countries submitted climate strategies (Nationally Determined Contributions) to support the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement objective. Many countries' strategies include emissions reductions by 2030 to limit future global warming to less than 2° C. However, even if successfully implemented, these pledges would only cut global emissions by about one-third of the amount required, so more ambitious targets are necessary.

From a climate perspective, the IMF sees a carbon tax as the most effective mitigation instrument to achieve these commitments (IMF 2019a[24]). It finds that emissions from flaring are feasible to tax because they are measurable, though safeguards may be needed to avoid creating perverse incentives for more venting. However, countries' circumstances vary and the IMF is ready to help individual countries with tailored strategies and plans for 'macro-critical' climate change.

For the energy sector, reducing gas flaring can help countries to achieve their NDCs—for example, Yemen (240 per cent of targets), Algeria (197 per cent), and Iraq (136 per cent). Countries which could meet a substantial portion of their NDC targets with gas flaring reductions include Gabon (94 per cent), Algeria (48 per cent), Venezuela (47 per cent), Iran (34 per cent), and Sudan (33 per cent).

Since the Paris Agreement was signed in 2015, the number of carbon pricing schemes has increased from 38 (covering about 12 per cent of global annual GHG emissions) to 57 (more than 20 per cent of global annual emissions). Singapore was the first country in South-East Asia to introduce a carbon tax, starting from 2019, at S$5 tCO2e. It covers the six greenhouse gases currently covered by the UNFCCC/Kyoto Protocol. The rate will be reviewed in 2023, with plans to increase it to $10–15 per tonne by 2023.

Notwithstanding the growth in carbon pricing, the IMF finds that action to date on carbon taxes has been 'inadequate'. The average global carbon price is $2/tCO_2$ (IMF 2019b). It recommends that achieving the Paris Agreement targets will require policy measures on a much more ambitious scale, including an immediate global carbon tax that will rise rapidly to $75/tCO_2$ in 2030.

The High-Level Commission on Carbon Pricing similarly concludes that the 'explicit carbon-price level consistent with achieving the Paris global warming target is at least $40–80/tCO_2$ by 2020 and $50–100/tCO_2$ by 2030, provided a supportive policy environment is in place' (CPLC 2017). In 2019, only a handful of countries and regions were in this range, including Norway ($49) and the EU ($25). In June 2020, BP became the first international oil and gas company to raises its internal carbon price to $100/tCO_2$, up from $40/tCO_2$.(Moody-Stuart 2019). Comprehensive

[24] The paper presents a spreadsheet tool to analyse the likely impact on emissions, fiscal revenues, local air pollution, mortality, and other social impacts of different instruments, including carbon taxes, emissions trading systems, taxes on individual fuels, and incentives for energy efficiency.

carbon taxes can also raise a significant amount of revenue—depending on the country's energy mix, but typically 1–2 per cent of GDP for a \$35/tCO_2 tax in 2030 (Parry 2019, chart 2).

For the energy sector, given the scale of hydrocarbon flaring and venting, considerable economic value is forgone. Our previous paper finds that if 75 per cent of this global upstream gas could be captured and brought to market, it would provide \$36 bn of additional annual sales (at an average gas price of \$4/MMBtu). Most (85 per cent) countries that are flaring and venting hydrocarbons are low- and middle-income countries. This forgone revenue could generate considerable additional domestic resources for the governments of these countries.

CO_2 tax is a key instrument (and perhaps the most effective measure) to combat global climate change. However, the contribution of CO_2 to global SCAR from flaring is less than 10 per cent. Under perfect combustion, the contribution of CO_2 would be 100 per cent. Furthermore, the global warming (climate) component of SCAR from flaring (excluding health and regional precipitation effects) is less than 4 per cent. The greatest contributions to SCAR caused by flaring are from NO_X, SO_X, and BC, due to incomplete combustion and primarily impacting human health due to their toxicity. Therefore, fiscal measures for flaring should focus principally on the quality of flaring.

Taxation of flaring through general CO_2 measures wrongly assumes that flaring is not worse than full combustion from natural gas under economic use. Moreover, if flare combustion quality rises, so do CO_2 emissions at the expense of a reduction in more damaging chemicals. A fiscal policy that addresses flaring solely through CO_2 measures further risks operators venting instead of flaring, and by doing so avoiding CO_2 emissions at the expense of much greater damage to health, the environment, and the climate. Therefore, taxation of CO_2 emissions from flaring should be considered only in combination with other fiscal measures on flaring and venting emissions. Then a CO_2 tax will add value in further disincentivizing waste of APG as a natural resource as well as benefiting action against climate change.

6.2.2 Methane

The IEA sees methane emission avoidance as a major opportunity in reducing the short-term emission impact on global warming: 'even with an oversupplied gas market, reducing methane emissions from oil and gas operations is amongst the lowest of low hanging fruit for mitigating climate change' (IEA 2020b). Capturing these atmospheric emissions would support several of the UN SDGs, such as Climate Action (SDG13), Good Health and Well-being (SDG3), Affordable and Clean Energy (SDG7), Gender Equality (SDG5), and Sustainable Cities and Communities (SDG11).

In addition to the benefits to the climate, there are significant societal benefits in terms of human health and air quality if governments and regulators price in the cost of atmospheric emissions from the upstream oil and gas sector. Few countries directly tax methane and other non-CO_2 emissions (Rabe et al. 2020). Countries such as Norway tax CO_2, methane, and NO_X using CO_2e. In 2019, these taxes covered 63 per cent of GHG emissions, or around 80 per cent with emissions trading (ETS). In the US, almost all energy-producing states tax extraction of oil and gas through 'severance taxes', to capture public value from the permanent loss of a natural resource (see Box B). Methane emissions, however, are generally exempt through methane release exceptions. The logic in the US appears to be to avoid placing a financial burden on the oil and gas industry, unless it is on activities that create commercial value. There is also a disincentive in that if methane is captured and used commercially, the producer pays royalties to property owners as well as severance tax to the state government. The IMF finds that shale gas extraction does not warrant a significantly different fiscal regime than that recommended for conventional gas.

In 2019, the IMF (2019a) suggested that:

> If fugitive and venting emissions could be monitored on a continuous basis, an emissions tax would be the ideal instrument—monitoring technologies are advancing though currently provide only discrete measurements at a limited number of sites. One possibility for the interim might be to tax fuel suppliers based on a default leakage rate but allow rebates to firms that are able to demonstrate lower leakage/venting rates through mitigation and installing their own continuous emission monitoring systems.

The OECD similarly finds that if 'a tax could be placed on both CO_2 and methane emissions from oil and gas production, with a higher tax on methane, producers would then have a stronger incentive to flare or re-inject the methane emissions' (OECD Environment Directorate, undated).

6.2.3 Incentives

The IMF has reviewed fiscal regimes for shale gas development in ten jurisdictions, six in North America and four elsewhere (Algeria, China, Poland, and the UK), looking particularly at the issue of whether the sector requires fiscal incentives to encourage development that may not otherwise happen, for example due to higher costs or to low return on capital. It concludes that the sector does not 'need' either special incentives or a differentiated fiscal regime from conventional oil and gas. Moreover, the energy intensity in developing shale, the fugitive emissions of methane, and the scale of flaring all indicate that shale developments are contributing at least as much as conventional developments to emissions per unit of production and therefore do not warrant more favourable fiscal treatment.

The large increase in US flaring in recent years is the result of very many small-volume flares. Therefore, the regulations and fiscal measures should address the total volume of emissions (including flaring quality) and not just concentrate on limiting the emissions per flare. However, the Texas Railroad Commission is reported to have approved more than 27,000 flaring permits[25] without denying a single flaring permit in years: 'receiving a permit to flare unwanted gas has been a mere formality' (Cunningham 2020). Moreover, a 2020 survey by the EDF found that 11 per cent of flares in the Permian Basin were malfunctioning or unlit, causing at least 7 per cent of Permian natural gas to be vented, 3.5 times more than the EPA assumes (PermianMAP 2020).[26]

The World Bank GGFR recommends that fiscal terms should encourage gas utilization investments. Special fiscal treatment can help companies with high up-front capital costs and (relatively) lower rates of return compared with oil production. Other incentives to reduce flaring

[25] In a follow-up development to the flaring example described in our first flaring and venting paper (involving the Texas Railroad Commission, i.e. the state regulator, on flaring permits handed to an oil and gas company for an asset that was already hooked up to a gas evacuation system), the same issue was subsequently sued in court. In its court petition, the suing party Williams (the pipeline company) accused the Texas Railroad Commission of 'an evolved practice at the Commission under which it has not denied any of the more than 27,000 requests for flaring permits received in the past seven years' (Collier 2019).

[26] The Permian Basin is a major oil shale development that in 2017 contained 45.5% of the total number of flares in the US and contributed 36.8% to the total US volume flared. Our assessment of US emissions that are the basis of SCAR estimates follow the emissions as recorded by the EPA. We have already reported that these data are partially based on 'emission factors' that may not follow actual performance trends. We have not corrected the flare quality data (as expressed by SCAR) for the observations by EDF and others that indicate that flare quality is significantly less (and SCAR higher) than assumed.

and venting could be defined for developing common infrastructure, improving access to markets (transportation and domestic market development), benchmarking, and sharing best practice. GGFR provides good practice case study examples and has worked with the EBRD to develop successful demonstration projects for the commercialization of natural gas.

Technology development and implementation is another opportunity. Norway is an example (see Box C) of how the rate of carbon taxes on oil and gas production, which increased again in 2014, further incentivized companies by making flaring reductions lucrative and causing companies to invest in new technologies. In April 2020, Canada announced a C$750 m Emissions Reduction Fund to reduce emissions in Canada's oil and gas sector, with a focus on methane (CCAC Secretariat 2020a). The fund will provide repayable contributions to onshore and offshore oil and gas firms to support investments in technologies to reduce GHG emissions. In January 2020, new federal methane regulations came into force to cut oil and gas sector methane emissions by 20 million tonnes a year by 2025. Governments could also reduce barriers to provide tax credits for imports of certain technologies and equipment that could make APG developments commercial, when such equipment cannot be fabricated locally.

Finally, governments could stimulate local gas market development, or, in the case of gas-to-wire, electricity market development by providing gas price guarantees or electricity feed-in tariffs over a limited period of time to stimulate infrastructure development while reducing investment risk. International financiers and organizations could provide further resources to facilitate development while reducing wasteful emissions.

6.2.4 Penalties

Countries that have been at the forefront of applying fines on volume of gas flared or vented are Norway (see Box C), and the US in relation to the Outer Continental Shelf (see Box B), both with strong and empowered regulators, and Nigeria (see Box D).

Nigeria is an example of penalties being set at levels that are a realistic deterrent, used in combination with incentives. The Nigerian Gas Flare Regulation, approved in 2018, raised the penalty from US$0.10 to $2 per thousand standard cubic feet (kscf) of gas flared or vented within an oil mining licence. Initial analysis suggests that the government received additional revenues of US$120 m in 2019 (Hedley 2020). In the same year, taxes were raised again to $3.50/kscf, with an estimated increase in revenues of $270 m.

The Nigerian government is currently seen as a most advanced nation for its measurement of flare data from the VIIRS satellite for all its upstream oil and gas operations and use of this information as a source of tax income. The Gas Flare Tracker was developed with support from the UK's Department for International Development (DFID) and is managed and maintained by Nigeria's National Oil Spill Detection and Response Agency (NOSDRA). For example, according to the Flare Tracker website, Shell's Bonga development flared 33.4 MMscf of gas in the seven-year period March 2012 – May 2020, valued at US$116 m and with penalties payable at $66.7 m (unadjusted for the latest increase in tax rates). Comprehensive and accurate measurement of flaring data by source and owner is therefore a major source of tax income for the government of Nigeria; see Box D.

Box D. Nigeria: an innovative Gas Flare Tracker provides tax revenues and societal benefit

Nigeria is one of the most successful countries in reducing its emissions. In 2019, Nigeria ranked globally as the seventh-largest gas flaring nation, down from second in 2005. This is due to a combination of fiscal measures targeting flaring, regulatory action (including mandatory reporting of flaring and methane emissions), commercialization of gas for export (Nigeria is the world's fifth-largest LNG exporter), and domestic consumption.

Natural gas flaring and venting reduction framework

- **Improved measurement.** With the support of DFID, Nigeria developed a reliable Gas Flare Tracker. This is based on (1) satellite data giving daily flare volume measurements from 280 data points in the Niger Delta, and (2) development of a reliable calibration method between this satellite-observed data and reported flare volumes supplied by oil companies to the NNPC. Historically, these data have been difficult to compile because of the multitude of sources, geographical distribution, and difficulty of access. Remote sensing technologies by satellite have progressed sufficiently to be utilized for gas flaring assessments; see also Sections 3.2 and 3.3.

- **Accountability, transparency, and reporting.** Data from the VIIRS satellite has proven successful as a flare-assessment system across Nigeria. The Tracker was created as a source of open data for citizens and community organizations. The flaring data is publicly available on the websites https://nosdra.gasflaretracker.ng and https://gasflaretracker.ng, displaying a map that shows all the gas flares in the region, with details per asset and over time about the gas being burned.

- **(Small-scale) gas development and monetization.** Despite the penalty (see below), in 2019 a significant proportion of APG continues to be flared. The Nigerian government has shifted its approach to actively promote gas production by providing larger fiscal incentives for gas compared with oil. This encourages companies to develop downstream gas networks and markets. In 1989, the NNPC and joint venture IOCs began development of the Nigeria Liquefied Natural Gas (NLNG) plant. The plant came into production in 1999 and is currently operating six LNG trains with a capacity of 22 Mtpa. In the period 1999–2012, NLNG converted 104 bcm of APG to export LNG/natural gas liquids (NGL), products which otherwise would have been flared. In May 2020, Shell announced that a final investment decision had been taken to further increase NLNG's capacity by 8 Mtpa from a seventh liquefaction train (Train 7, 4.2 Mtpa) and the de-bottlenecking of the existing facilities (3.4 Mtpa), at an expected cost of about US$10–12 bn. This capacity increase will provide further opportunity to reduce APG flaring. Of the 183 gas-producing fields, 48 fields produce 90 per cent of all gas, with the top ten producing fields making up 55 per cent of overall production. The remaining fields produce gas at an average rate of less than 20 MMscfd. Of the four types of (oil and) gas operations in Nigeria, the NNPC-IOC joint ventures dominate gas production. The multiple pipelines and dedicated gas-processing plants make LNG production and loading possible, even when one or more pipelines are damaged. The most important customers for gas are NLNG, the Nigerian gas company (NGC), and the Eleme Petrochemicals Company Limited (EPCL). Further domestic opportunities to monetize APG now being flared are: the electrification of offshore facilities using APG as feedstock for power, the promotion of CNG as a low-cost, low-emission fuel for transport, and the electrification of areas with power shortages.

- **Regulation and fiscal framework.** Nigeria is one of the few countries which set gas flare emission limits for upstream operations, having done so since 1969. It is similarly one of the few to use taxes as a disincentive to flare. The Petroleum (Drilling and Production) Regulation Decree, 1969 (which also governs the natural gas sector), provides that the licensee/lessee can flare gas for five years, after which a feasibility study for gas utilization is required. The Petroleum Amendment Act, 1973, gives the federal government the right to take APG at the point of flaring without cost, to ensure that it is used instead of flared. The Associated Gas Re-Injection Decree, 1979, aimed at banning flaring from 1984 unless permission is granted. In 2017, to address the dual challenge of decarbonization and advancing energy access, the government launched the National Gas Master Plan to drive investments in the domestic gas sector, and the Nigeria Gas Flare Commercialization Programme. This raised the penalty for any gas flared from US$0.10 to $2/kscf; it increased again in 2019 to $3.50/kscf.

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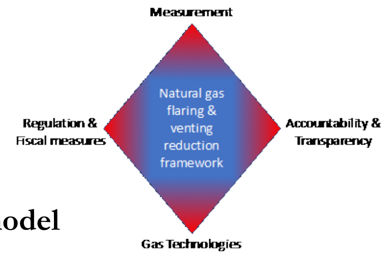
6.3 Way forward on regulatory and fiscal measures to reduce emissions from oil and gas operations

- A CO_2 tax is a key instrument (and perhaps the most effective measure) to combat global climate change. Taxation of CO_2 emissions from flaring should also take account of the different chemicals and their different impacts, not only those that are climate-related but also those impacting air quality, health, toxicity, and precipitation. Then a CO_2 tax will add value by both further disincentivizing waste of APG as a natural resource and encouraging beneficial actions against climate change.
- The IMF proposes that in order to address methane leakage, fuel extraction could be taxed based on a default methane leakage rate, with rebates to companies that demonstrate, via continuous monitoring, a leakage rate below the default rate.
- Fiscal measures for flaring should focus principally on the quality of flaring. A fiscal policy that addresses flaring solely through CO_2 measures further risks operators venting instead of flaring, and by doing so avoiding CO_2 emissions at the expense of much greater damage to health, the environment, and the climate.
- Carbon taxes can also raise a significant amount of revenue, typically 1–2 per cent of GDP for a US$35/t$CO_2$ in 2030. This can support the UN SDGs.
- For the energy sector, given the scale of hydrocarbon flaring and venting globally, captured gas would provide $36 bn of additional annual sales, if 75 per cent of global upstream gas could be captured and brought to market.

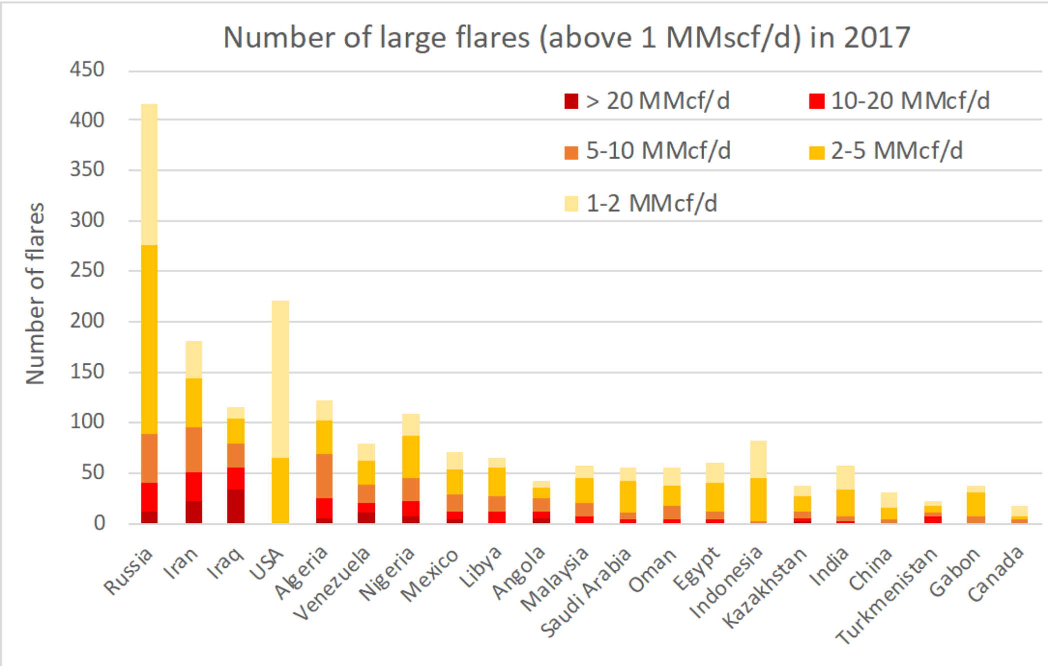


7 Opportunities for implementing the flare and vent reduction model

Having evaluated the four elements of the flare and vent reduction model (flare and vent measurement, accountability and transparency, gas monetization technologies, and regulation and fiscal measures) in the previous sections, we now focus our attention on how these can be combined in a consistent approach to fully operationalize the model and make a significant impact in the reduction of APG flaring and venting.

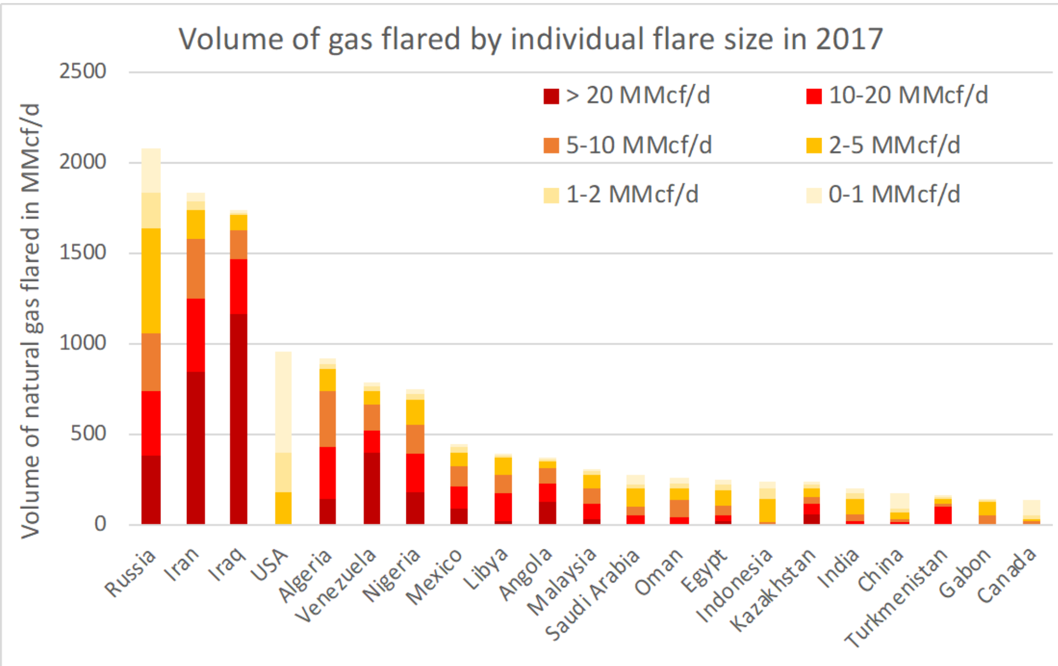
In 2017, VNF registered 10,820 individual flares globally. Part of the challenge, therefore, is to identify those flares that are the most likely candidates to be converted into gas development opportunities *and* that have the largest potential impact in terms of SCAR reduction. As shown in the DNV GL 2015 study, flare size and distance to market are the key two criteria for commercial gas monetization (see Figure 20). The VNF dataset makes it possible to assess flares by their size (see Figure 18) and to identify the locations of each of these flares. To assess the applicability of the technical gas monetization options in Table 3, we need to assess individual flare sizes and opportunity for gas aggregation of nearby flares. Opportunities for large-scale APG aggregation and development primarily exist in countries with the largest number of large flares (Figure 22) and the largest APG volumes consumed by large flares (Figure 23).

Figure 22: A sample of the largest individual flares in 2017, categorized by flare size



Source: authors' illustration based on 2017 VIIRS data.

Figure 23: Volumes flared by top flaring countries, categorized by flare size



Note: this figure shows the amount of gas flared for the same top 21 countries, clearly highlighting where large flare reduction measures can make the biggest emission volume impact.

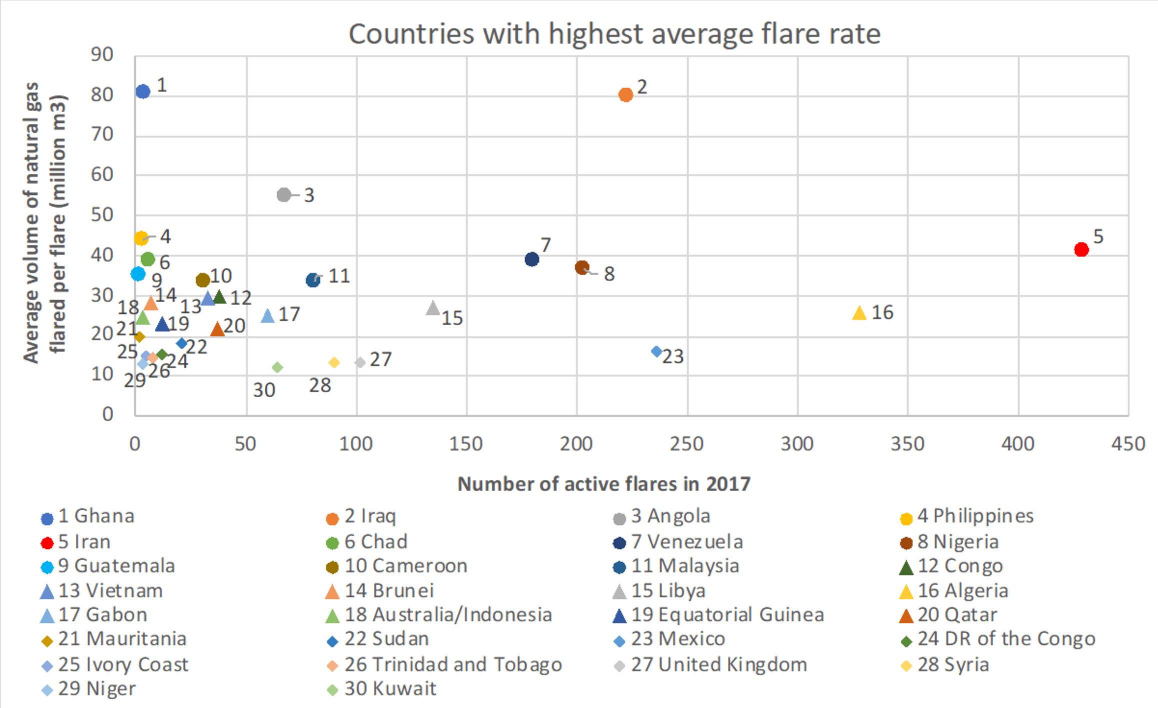
Source: authors' illustration based on 2017 VIIRS data.

We have made this flare size assessment for each of the 105 countries that had flares identified by VNF in 2017. As a follow-up to this work, we propose to superimpose on the VNF data for large flares (and densely clustered flares) additional spatial information such as population density and oil and gas production acreage. Population density information would allow us to link spatial and volume data of flares with potential market opportunities for the gas products summarized in

Table 3. The proximity of local populations to flares and the dispersion of chemical releases in the atmosphere also provide another dimension to the SCAR analysis of flares. We intend to further prioritize the eradication of flares based on their likelihood of causing disproportionate harm to local populations in terms of health. Adding spatial data on oil and gas licences allows the aggregation of flare data by company as an independent measure, for example to verify TCFD disclosures by companies. GGFR publishes annually the volumes of gas flared by country. There is no public information available which gives detailed flare data by company. By combining and publishing data for large flares with oil and gas production acreage, the transparency and visibility of these data (e.g. in a ranking exercise) puts peer pressure on companies to increase efforts to reduce flare volumes.

A further key area of concern that we have frequently highlighted in our reports is the occurrence of super-emitter flares due to bad flaring quality (as exemplified in Figures 8 and 9). In our analyses, we have noted that VNF may underestimate the amount of flaring if a flare's heat and light emissions are frequently obscured by smoke. Further work is needed to correctly assess the flaring rate of smoke-obscured flares. Furthermore, having identified the detailed flare locations by VNF, there is an opportunity to combine this information with other satellite data such as OMI instrument data from on board NASA's Aura satellite. Such an assessment was done for an offshore flare in Mexico (see Figure 11) and NO_2/SO_2 emissions were combined and compared with VNF data. In another example described in our first flaring paper, we highlighted research that was done to identify the transportation of BC into the arctic region from flares in North Dakota (Li et al. 2016). Combining sensor input not only provides more accurate rate estimates, but can also provide a detailed picture of individual chemical releases that determine flare quality and SCAR. A key objective of this further work would be to determine individual SCAR values for super-emitter flares based on their flare emission composition as well as their emitted volume. We have shown that because of poor flaring operations, the social cost per volume flared is 12.6 times higher than under perfect combustion. Poor flare operations negate most of the benefits that flaring has over venting (SCAR for venting is 16 times higher than perfect combustion); see Figure 2. 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.

Figure 24: Overview of the countries with the highest average flare volumes in 2017



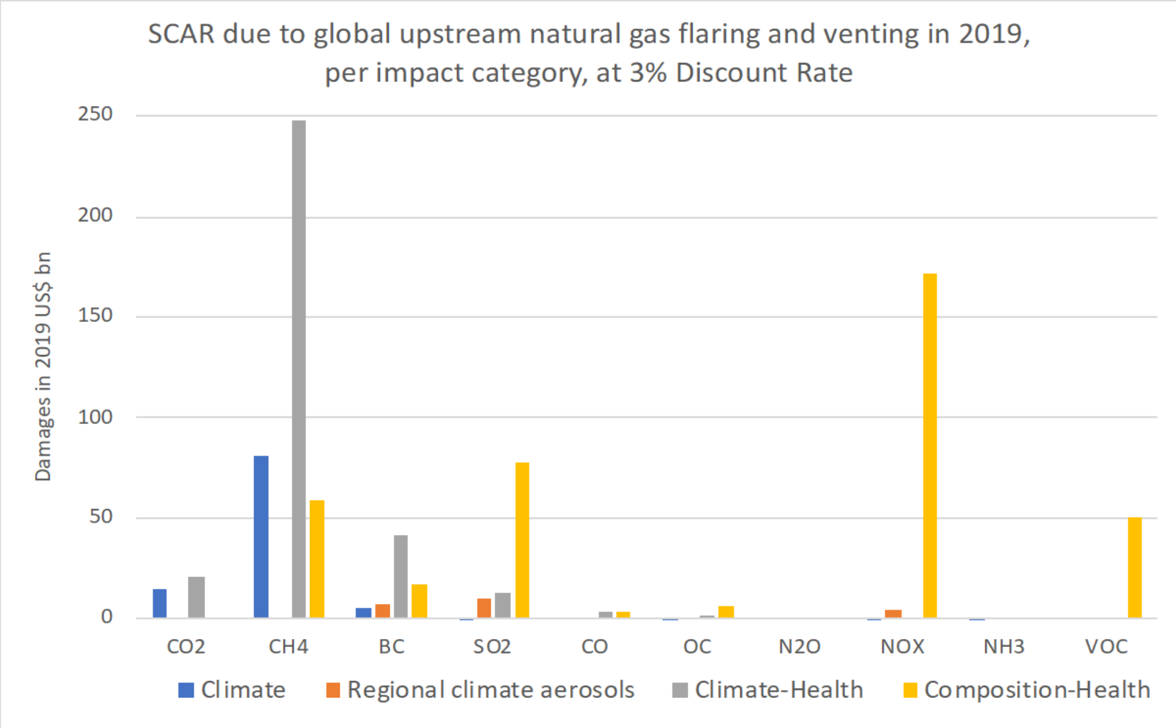
Note: circles represent flares larger than 30 million m^3 per annum, triangles those 20–30 million m^3 per annum, and diamonds those less than 20 million m^3 per annum. Although flares are often assessed by volumes emitted by country or by largest flare size, we note interesting outcomes when we evaluate countries with highest average flare rates. Apart from countries with high oil production and an underdeveloped gas economy (Iraq, Iran, Angola, Venezuela, Nigeria), we also see countries like Ghana, Philippines, Chad, Guatemala, and Cameroon with little oil production and few, but high-rate, flares.

Source: authors' illustration based on 2017 VIIRS data.

In this report, we have mostly focused on flaring data, although gas monetization efforts also need to include opportunities and sites where large amounts of APG are being vented. The IEA (2020a) estimates that around 40 per cent of the 80 Mt of methane emissions that occur in global oil and gas operations today could be avoided with measures that would have no net cost.

With the significant progress made on identifying flares from satellite data, there is a risk that oil and gas operators may avoid flaring and opt to vent instead (see Section 6.1). It is important that methane detection by satellite, as done by GHGSat-D Claire, continues and is augmented by the recently launched GHGSat Iris. Iris is expected to significantly increase both the volume and the resolution of methane detection. Another satellite, MethaneSAT, set to launch in 2022, will take measurements at more than 300 times the resolution of current instruments, dramatically reducing the cost of measuring methane emissions from point sources. It is of great interest to detect methane emissions from oil and gas installations. This will not only identify the emission locations of the largest contributor to SCAR from venting and flaring (see Figure 25); it will also help to establish potential relationships between flaring and venting emissions. For example, assessing flares for methane emissions can point to incomplete combustion and badly operated flares.

Figure 25: Methane contributes the most to the global SCAR from flaring and venting



Source: authors' illustration based on IEA (2020b), GGFR (2020a), Shindell (2015), and Romsom and McPhail (2021).

Based on the research described in this paper, we have made a high-level assessment to guide further work in developing market opportunities—new projects—for APG currently flared. Political factors, country risk, and other considerations will have to be included in the decision-making process, to determine which of these potential opportunities are to be matured first into flare capture projects. Table 5 provides an impression of the approach that could be followed to define potential gas monetization options for different flare sites. We identified the potential opportunities in Table 5 (and exemplified in Figures 26, 27a, and 27b) based on initial screening studies of flaring sites and their proximity to potential areas of gas demand. A ranking methodology is being developed to identify the most promising of these opportunities for further assessment and maturation.

Table 5: Summary of some key monetization opportunities for flare gas

Gas options	In-field applications	Pipeline	Gas-to-wire	CNG	Mini-LNG	Mini-GTL	Petro-chemicals	LNG export
Russia 2,080 MMscfd		Connect supply to pipelines			Road transport applications		Large-scale flare gas aggregation	Yamal expansion
Iran 1,838 MMscfd			Replace fuel oil for power generation	52 MMscfd (37 flares are 1–2 MMscfd); Iran 4.1 m CNG vehicles				Gas flares >2 MMscfd: 1,740 MMscfd (10 Mtpa)
Iraq 1,739 MMscfd			Replace fuel oil for power generation					>2MMscfd: 1,710 MMscfd (10 Mtpa)
USA 956 MMscfd	Fuel for high-activity shale production	Connect supply to (new) pipelines	Further phase out coal for power		Transport by road, river, lake, and train			Increase APG supply to existing LNG
Nigeria 749 MMscfd	Electrification of oil and gas fields		Electrical energy access	Expand CNG vehicles (now only 3,800)				Increase APG supply to existing LNG
Indonesia 240 MMscfd		Facilitate open access to pipelines at low tariffs for APG	Electrical energy access	Island energy access with maritime transport of CNG			Production of fertilizer through methanol from APG	
India 200 MMscfd	Offshore electrification: 70.5 (81.4) MMscfd flared on 10 (21) platforms (80km radius)		Electrification of agriculture areas in Rajasthan & Mehsana with 2.7 and 3.0 MMscf flares	32 MMscfd (21 flares are 1–2 MMscfd) India has 1.8 m CNG vehicles				
China 178 MMscfd	Offshore electrification with 14 + 3 MMscfd flared on 1 + 4 platforms		City power to Aksu and Kuqa 1 m people near Tarim oil basin flares 45 MMscfd	41 MMscfd from 56 flares 0.5–1.5 MMscfd, 4.1 mln CNG vehicles	Small-scale LNG for road transport is common in China			
Gabon 145 MMscfd	Offshore electrification 23.5 MMscfd flared on 4 platforms (in		34 MMscfd, 180 km from Port Gentil, replace diesel in existing	6.2 MMcf coastal flare at Port Gentil to supply CNG for marine operations				1 Mtpa FLNG to aggregate onshore and offshore APG (+

	10 km radius)		power station					reservoir blow-down)
Argentina 59 MMscfd	Fuel for high-activity shale production in Vaca Muerta	Under-utilized open-access gas pipelines to Uruguay Chile, Brazil	Expansion of gas-fired power capacity	27 MMscfd from 28 flares 0.5–2 MMscfd and 2.5 m CNG vehicles				Commingle with dry gas production (6 Mtpa)
Ghana 31 MMscfd	Offshore electrifica-tion - 31 MMscfd flared on 3 platforms			Energy access with maritime CNG transport to onshore				
Chad 23 MMscfd			17.7 MMscfdl energy access in Bousso city 15k people			17.7 MMscfd convert to fuel; 44 km from Bousso		

Source: authors' construction.

Figure 26: Example of Pakistan's largest flare near Sanghar, globally ranked 355th in 2017

Note: this flare consumed 9 MMscfd of natural gas in 2017, surrounded by agricultural land, towns, and villages (indicated by the white circles in the image) within a 2 km radius. The nearest settlement is 350 m from the flare (the nearest house is at 250 m). Gas flares are often surrounded by agricultural land, towns, and villages. Flare emissions negatively affect the growth of healthy crops. Identifying large flares which are also close to market, and close to population, maximizes the impact of gas monetization. The screening and ranking of these opportunities to improve the health of the local population offers also gas monetization opportunities such as CNG schemes. These can provide clean fuel for agricultural equipment such as engines and irrigation pumps that could result in a greater yield of local agricultural produce.

Source: authors' illustration based on a combination of Google Earth images with 2017 VIIRS data.

Figure 27a: Example of a remote Gabon oil installation and 5.8 MMscfd flare, globally ranked 593rd in 2017

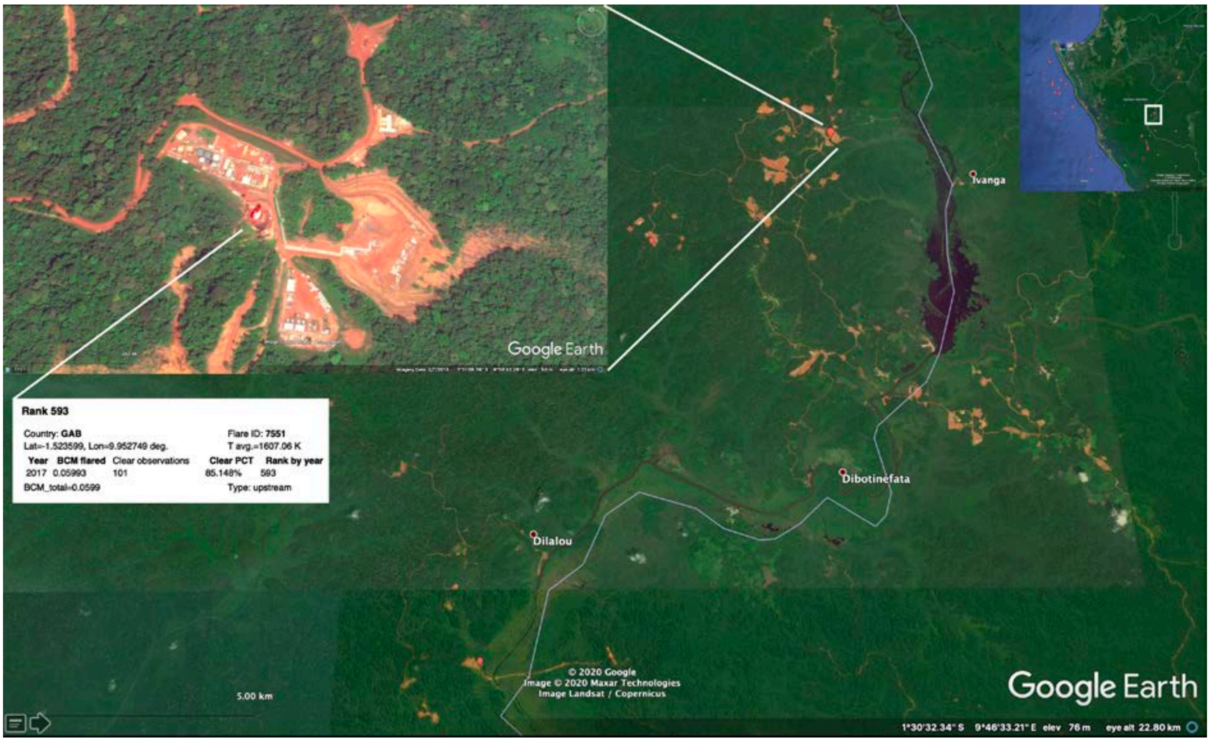


Figure 27b: Contrasting example of a Gabon 6.2 MMscfd gas flare on the outskirts of Port Gentil, globally ranked 543rd in 2017

Note: within a 500 m radius of the flare (yellow circle in Figure 27b), many houses can be observed. The nearest homes are at 170 m distance.

Source: authors' illustration based on a combination of Google Earth images with 2017 VIIRS data.

8 Conclusions, solutions, and recommendations

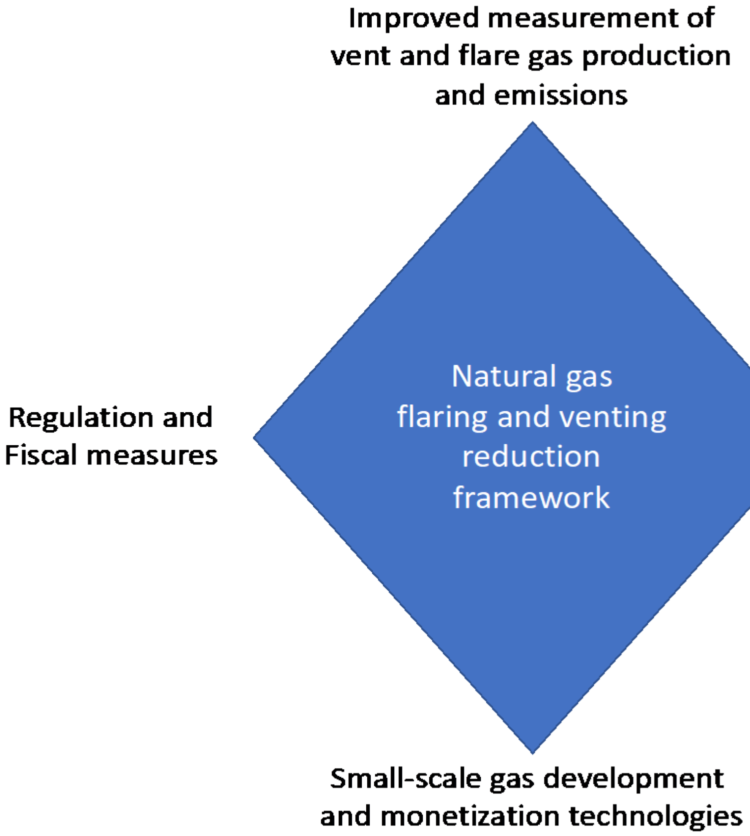
The main purpose of routine flaring and venting is to get rid of APG, a by-product in the production of oil. In our first flaring paper (Romsom and McPhail 2021), we established the scale and scope of and impact from hydrocarbon flaring and venting. Linking separate databases, GGFR (to determine CO_2 from flaring), IEA (methane from venting and leaks), EPA, and other data sources (BC, NO_X, and SO_X, VOCs, organic carbon, CO, NH_3, and N_2O), that paper provided an integrated assessment of natural gas flared and vented by the oil and gas industry that includes the amounts of chemicals released in the atmosphere. The paper found that the **scale** of natural gas flared and vented has not reduced since the year 2000. Methane emissions increased between 2000 and 2019. In 2019, the amount of natural gas flared (3.7 per cent) and vented (3.1 per cent) in global upstream oil and gas operations was 6.8 per cent of total production. Since natural gas provides 23.6 per cent of global primary energy demand (versus oil 32.7 per cent), gas should not be treated as a waste product. The **scope** of gas flaring is broad. In 2017, gas flaring occurred in 105 countries around the world.

A major deliverable of the first paper was to show the resulting atmospheric releases and their social impact in a consistent representation. To assess **impact**, we need to recognize that different emissions affect climate, air quality, health, and environment differently. These wider-ranging impacts from this broader spectrum of releases are captured in a multi-impact economic valuation framework. The social cost of atmospheric release (SCAR) assigns a social cost per ton for each individual chemical release.

Where gas is flared efficiently, i.e. with near-perfect combustion, it has significant benefits over venting (the SCAR for venting is 16 times higher than perfect combustion). However, poor flare operations negate most of the benefits, and the actual social cost per volume flared is on average 12.6 times greater than under perfect combustion. Despite uncertainty ranges in SCAR estimates, the SCAR methodology provides a solid basis on which to estimate the social cost on climate, environment, and health, and demonstrates the imperative of reducing these emissions. Flaring, venting, and leaks contribute more than half (54 per cent) of the total SCAR from all natural gas produced and used.

In this second report, we have combined this socioeconomic cost analysis with a 'Diamond' model (see Figure 28) that provides the means to construct an abatement strategy for capturing economic and social value from hydrocarbon gas 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 vent and flare emissions; (3) small-scale **gas development and monetization technologies**; and (4) **regulation and fiscal measures**. An overview of the socioeconomic impact on a local, national, and international scale from gas flaring and venting in terms of opportunity and externality cost is set out in Table 6.

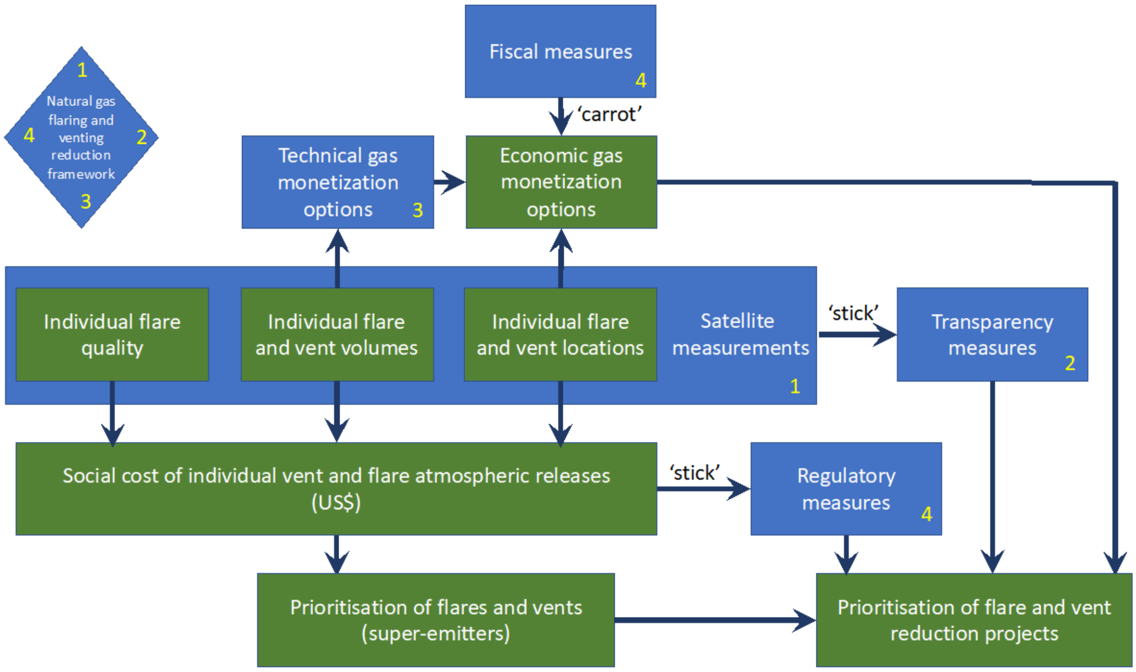
Figure 28: Integrated framework 'Diamond model' to end routine flaring and venting



Source: authors' illustration.

The four elements of the Diamond model are interrelated, and implementation of each element can benefit the effectiveness of the other elements. Figure 29 depicts a flowchart for the concerted implementation of the Diamond model.

Figure 29: Flow chart for the implementation of the Diamond model to reduce flaring and venting of natural gas



Note: the combination of the elements of the 'Diamond' model (blue boxes) drives the identification and prioritization of flare and vent reduction projects that capture the economic and social value from natural gas flares and vents. **Satellite measurements** (1) of flare and vent volumes help to identify the scale of each flare and vent opportunity and what **technical solutions** (see Table 3) could be applicable (3). When this assessment is combined with further information on flare locations, the type of gas monetization and the distance to market can be assessed, further constraining the potential **economic** gas optimization options. Applying **fiscal measures** to flaring and venting (4) can positively influence the commercial break-even point for monetization. In addition to the pursuit of commercial opportunities, satellite measurements can also be utilized to assess the **social cost** of individual vents and flares to prioritize **super-emitter** release sources. **Regulatory** (4) and **transparency** (2) measures can provide further incentives (complementary to the commerciality of the flare and vent resources) to **prioritize flare and vent reduction projects**.

Source: authors' illustration.

8.1 Capturing economic and social value for national government and society

8.1.1 Government revenues

The scale and scope of upstream flaring and venting illustrate the opportunities for government revenues. If 75 per cent of the gas flared and vented were to be captured from upstream oil and gas operations, it would provide an **additional natural gas sales value** of US$36 bn each year, assuming an average gas price of $4/MMBtu. Most countries that are flaring and venting are low- and middle-incomes countries.

A key driver for the Nigerian government in developing an innovative Gas Flare Tracker is the potential **tax income** that is levied on oil and gas companies, based on their volume of natural gas flared. The flaring data are publicly available on a website, with a map that shows all the gas flares in the region, with details per asset and over time on gas being flared. Consequently, there is no longer a dependency on companies to **self-report**. The potential for alternative use for the Nigerian gas currently flared is substantial: close to 28,000 gigawatts of power could be generated, which could provide 40 per cent of Nigeria's electricity demand.

Open-source satellite data and transparency measures 'level the playing field' for government and civil society in terms of access to information on how much natural gas is flared each day. This can also be used to determine the basis for assessing **compliance with emission volume regulations**, as well as for **taxation and/or fines**.

Flaring and venting emit a range of different chemicals, each with different SCAR impact. Non-climate damages, and particularly health impacts, are much larger than climate damages. The WHO finds that air pollution is the leading environmental health risk that humans face. One in eight premature deaths is due to air pollution, largely a result of increased mortality from stroke, heart disease, lung disease, and cancers. Many of these air pollution sources also cause unwanted climate change effects. Hence, fiscal measures targeted at such pollutants can support improved life expectancy, raise revenues for government, reduce health costs, and support climate mitigation.

Norway, ranked 15th among global oil producers in 2014, levies taxes based on the compositions and volumes of different atmospheric chemicals emitted. It has applied a NO_X emissions tax since 1997. Its 1991 carbon tax also covers natural gas that is emitted directly into the atmosphere (such as vents and leaks). These fiscal measures caused industry to develop technologies to establish methane capture rates above 99.8 per cent. Few other countries tax methane (and other GHG emissions). If they do so, it is usually on the basis of CO_2e. This does not capture the full social cost, since the SCAR of methane is much broader than its global warming impact as expressed in CO_2e.

8.1.2 Solutions and recommendations

- Methane and other non-CO_2 releases contribute 52 per cent to the total SCAR from all produced natural gas. In the absence of metering (e.g. of methane emissions), **taxes** can be levied assuming default leakage rates, with **rebates** given to operators that demonstrate, via continuous monitoring, lower leakage.
- **Taxes levied on atmospheric emissions** that reduce flaring and venting emissions have a positive effect on public health (particularly in the areas of respiratory diseases and cancer), and such tax proceeds can be used to further improve public health expenditure, which stimulates higher GDP growth due to higher productivity.
- **Tax proceeds** on venting and flaring could be used to promote efforts that optimize **the utilization of gas**, such as infrastructure and gas market development, in support of solutions to discontinue venting or flaring. This could include waivers on import duties for technologies and equipment that could make APG developments commercial, when such equipment cannot be fabricated locally.

8.2 Capturing economic and social value for communities

Flare and vent rates and distance to market are the two key criteria for commercial gas monetization. **Flare measurement** and identifying the location of the almost 11,000 individual gas flares in 2017 enables the identification of the most likely opportunities for gas development and those that have the largest potential impact in terms of SCAR reduction.

Costs for small-scale **gas monetization** have reduced significantly through scalable and modular design optimization, with applications that are containerized and truck-mounted. Small-scale gas monetization of APG can also contribute to providing energy access to agricultural and remote communities in developing countries, supporting UN Sustainable Development Goals (e.g. SDG7). For example, CNG in developing countries is increasingly used as an alternative automotive fuel. It is also being used as a gas storage solution, particularly as a back-up option for (peaking) power plants. CNG can now be transported by maritime carriers. In 2016, the world's first CNG carrier with a CNG carrying capacity of 25 MMscf was launched to supply the island of Lombok in East Indonesia with natural gas for power generation from fields in East Java. Much larger CNG carrier designs (200 MMscf) are in the process of being constructed.

Opportunities for large-scale **APG aggregation and development** exist primarily in countries with many large flares within relative proximity, such as Iraq, Iran, Venezuela, and Nigeria. The global 700 largest flares consume 60 per cent of all natural gas flared; in just 12 countries, the top 100 global flares consume 27 per cent of all flared gas.

A sample of large flares in Gabon, Nigeria, and Pakistan shows that in 2017, many are located close to villages, towns, and agricultural land. In Pakistan, a flare measuring 9 MMscfd of natural gas in 2017 is surrounded by agricultural land, towns, and villages within a 2 km radius. The nearest settlement is 350 m from the flare and the nearest house is at 250 m. Similarly, a large 6 MMscfd upstream flare on the outskirts of Port Gentil (Gabon) shows many houses within a 500 m radius of the flare, with the nearest homes at 170 m distance. Table 5 illustrates, for example, that 17.7 MMscfd would provide energy access in Bousso city, Chad, for 15,000 people. The eradication of flaring and venting near communities can provide disproportionate benefits in terms of **air quality (health)**, as well as **commercially** as a result of small distance to market.

Combining **satellite measurement** data to identify large flare volumes and poor flare quality (NO_X/SO_X) allows for the identification of **super-emitter flares**. Particularly, when further combined with additional spatial information such as population density, this allows the prioritization of eradicating flares in terms of overall SCAR on health. For example, BC, a known carcinogen with health impacts, and organic carbon each have a significantly greater SCAR per ton than either CO_2 or methane. Capturing these emissions would support SDGs that are linked to air quality: Climate Action (SDG13); Good Health and Well-being (SDG3); Gender Equality (SDG5); Sustainable Cities and Communities (SDG11); and Agriculture (SDG2).

Technology developments for mini- and micro-scale LNG have enabled the monetization of significantly smaller natural gas resource volumes, such as flares. With the implementation in 2020 of stricter emission standards by the IMO in ECAs, the number of LNG-fuelled and LNG-ready ships is expected to grow significantly; this creates the opportunity for LNG bunkering infrastructure at many waterways and coastal locations.

8.2.1 Solutions and recommendations

- Reducing flaring and venting, particularly near communities, would have a significant positive impact on health and support the achievement of SDGs.
- By combining analysis of small-scale gas monetization options, the indicative unit costs of each **technology**, and **satellite measurement** data, it is possible 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
- Technical solutions exist for countries with a high flaring rate per flare, thus not requiring the aggregation of gas across different companies' oil and gas licences. Solutions for **gas monetization**, local energy access, and job creation lie within existing oil and gas contracts.

8.3 Capturing economic and social value for companies

8.3.1 Social licence to operate

Companies in countries such as Angola, China, Kuwait, Russia, Kazakhstan, and Qatar have over time increased oil production while also reducing gas flaring. Saudi Arabia, Norway, Kuwait, Qatar, and UAE 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).

NGOs working at local, national, regional, and global levels are **holding companies to account**. WWF in Russia and Stakeholder Democracy Network in the Niger Delta publish annual Environmental Performance Indices to track and **publish companies' performance** on gas flaring and oil spills and their impact on local communities. Clean Air Asia, a partner of the Climate and Clean Air Coalition, works on air quality throughout the Asia Pacific region, where 99 per cent of cities surveyed have levels of air quality below WHO guidelines. The Climate and Clean Air Coalition has launched the OGMP with the private sector, focused on emissions measurement, and the Global Methane Alliance with governments, to help them commit to ambitious methane reduction targets. In the US, the EDF, following a five-year multi-institute study, has raised funding to launch MethaneSAT to continuously map and **measure methane emissions**.

8.3.2 Access to capital

The OGCI, consisting of 13 international oil and gas companies set a target to reduce methane intensity in its members' operated upstream oil and gas assets by 2025. Companies missed an opportunity to speed up the reduction of methane emissions by not also applying the target to all company non-operated assets, as recommended by the UNPRI in 2015. The IEA finds that reducing methane emissions from oil and gas operations is among the 'lowest of the low hanging fruit' for mitigating climate change. **Corporate disclosure** using the industry-led TCFD framework would allow regulators and financiers to establish the extent of physical and energy transition risks for future investment.

8.3.3 Access to markets

Governments are increasingly questioning the role of natural gas in the energy transition. **Full value-chain certification** by accredited authorities provides market opportunities for gas. LNG buyers are likely to deem non-certified LNG cargoes or LNG that fails to meet emissions standards as having a lower value, as they will be required to buy higher levels of emissions offsets.

8.3.4 Solutions and recommendations

- Prudent operators must execute development plans and conduct operations that limit climate and environmental impact. Developments that **avoid routine flaring and venting** should be the minimum standard.
- The social cost of flaring increases significantly when the **quality of the flaring process** does not meet its 98 per cent destruction efficiency target. Investing in higher performance standards for atmospheric emissions is not 'gold plating' but an essential investment in companies' future competitiveness and their (social) licence to operate.
- An 'economically meaningful' **carbon price** would provide companies with the financial **incentive for investments** to discontinue venting or flaring and that optimize the utilization of gas. This benefits communities through APG resource utilization as well as SCAR reductions.

- Regulations requiring oil and gas companies to operate at higher standards that avoid emissions (e.g. **metered gas** streams to allow accurate measurements, **standard reporting format** to allow comparison and benchmarking across companies) are good for promoting industry competitiveness, energy efficiency, and the **development of new technologies**. These provide the platform for the (social) licence to operate for companies in this sector.
- The oil and gas industry needs to future-proof itself by adopting higher standards on atmospheric emissions than those adopted to date. The universal drive to **price externalities in** to the industry's performance measures is irreversible and is being called for by leading international oil and gas companies and the investor community. In the future, regulators and the public will hold companies to account for their past performance, based on the higher performance standards that will then be in place.
- Efforts to reduce SCAR from oil and gas operations **offer new areas of competitiveness** for companies to strengthen their value proposition to customers, investors, and society. Oil and gas produced with low emissions are likely to be higher-priced in the market.

8.4 Regulators and the role of finance

Regulation is the preferred instrument to 'universally discourage' gas flaring and venting. Some of the ten countries **with flaring regulations** have successfully reduced the volume of flared emissions. Between 2005 and 2019, Russia reduced gas flaring the most, followed by Nigeria, Kazakhstan, Angola, Uzbekistan, and Qatar. Canada, Indonesia, Brazil, and Australia maintained stable volumes, often with increased oil production. However, the scale and scope of flaring and venting remains large. Mexico and the US significantly increased the volume of gas flared.

There are 13 countries **with methane regulations**. Although the number has increased since the 2015 Paris Climate Agreement, the IEA and others are calling for more effective regulations in many key regions.

Norway's **regulatory** framework is key to the country's low fugitive emissions. Norway prohibits most forms of flaring, imposes steep fines on methane releases, and, since 1993, requires oil and gas operators to meter any flared gas. Together with a price on carbon and other GHG emissions (such as NO_X), this has caused industry to invest in developing technologies for s**mall-scale gas development and monetization**. Norway is a leading country in the development of small-scale LNG, including in transport. A large fraction of the global LNG-fuelled ships are in Norway, including ferries, tugboats, tankers, and offshore service vessels.

Russia adopted a decree in 2009 **requiring APG utilization** of at least 95 per cent from 1 January 2012 onwards. The Russian central government facilitated higher-priority access for APG producers to Gazprom's GTS. This resulted in a 77 per cent reduction in flaring from a major oil-producing region between 2012 to 2017. However, in 2017 19.9 bcm of the 98.3 bcm APG was still being flared (20 per cent). Without further fiscal measures for the above, there may be insufficient incentive for producers to invest. Under-investment is a key reason for the shortfall from the 95 per cent gas utilization target.

Financial regulators in almost 70 countries, including the Monetary Authority of Singapore, are focused on the investment risks from 'stranded assets'—where investors have holdings that become unsellable because of climate change. Companies are to disclose in line with the recommendations of the TCFD, which has developed a standard framework for corporate disclosure. Climate metrics for energy companies include **reporting** upstream emissions from flaring and venting in their public financial filings. Financial regulators, including the European Central Bank, are committed to working with authorities to make the TCFD standards compulsory.

Investors and lenders are increasingly calling on companies and others to **disclose** annual carbon emissions, and to **publish** emission reduction targets and their plans for transition to a low-carbon economy. They are also calling for higher capital provisioning for banks with carbon assets.

The Institute for International Finance, which represents the interests of the finance industry across 70 countries, has expressed concern about national regulators and governments taking different approaches to climate change and the increasing number of different accounting and measurement standards. It calls on the G20 to build on the FSB/TCFD efforts to set **common standards and definitions** of green finance.

Fiscal policy is seen as having a key role in reducing emissions to reach Paris Agreement targets. As of 2020, carbon pricing schemes cover only 20 per cent of global emissions, with an average global carbon price of US$2/tCO2., far below the range of $40–80/tCO2 deemed necessary. Oil and gas companies are beginning to sharply increase the internal price they believe they will need to pay governments in the future for carbon dioxide emissions as calls for higher taxes intensify.

8.4.1 Solutions and recommendations

- Global public–private voluntary initiatives, launched over 15 years ago, to reduce both CO_2 and methane emissions have yet to realize their promise. Non-voluntary measures, such as **regulations, global (reporting) standards, and fiscal solutions**, are needed to drive absolute emission reductions, which are more effective than relative emission intensity targets. Regulations need to be sufficiently specific, enforceable by the regulator, and implementation practicable for the oil and gas industry.
- Global institutional investors find that voluntary corporate efforts to properly **track and manage methane leaks** remain weak, exposing investors to significant risk both at the company level and across their portfolios due to the associated impact on climate and health. A lack of corporate disclosure and **transparency** of emissions aggravates the investment risks from ‘stranded assets’.
- **Mandatory reporting** has been shown to reduce carbon emissions. The TCFD is considering requiring mandatory disclosure of climate and transition risk in companies’ public annual filings to provide ‘decision-useful’ information to investors and other financial services. More work is needed to develop atmospheric emissions reporting (specifying individual contaminants) that is consistent, accurate, detailed, and verifiable, preferably through a common format and third-party verification. This could build on the work of UNPRI institutional investors and NGOs, which provides guidance on how to apply the TCFD framework for disclosure on methane emissions.
- **Regulation** is seen as a key instrument to reduce flaring and venting. More work is needed to establish a consistent and aligned **global data base** on effective country regulations and other best practices to reduce emissions from flaring and venting through lateral learning.
- Regulators need an **‘all-of-government’ approach in developing and implementing regulations**, with the resources and authority to monitor flare and vent volumes and emissions. Relevant ministries and agencies, including financial supervisors and ministries of health, should be involved when the social cost of flaring is distributed across a variety of chemicals, particularly methane, BC, SO_2, NO_X, and CO_2. For venting, methane and VOC emissions account for 90 per cent and 10 per cent of social costs, respectively. Carbon (and other atmospheric releases) pricing creates incentives for operators to reduce gas flaring and venting volumes, as these improve the commercial returns for gas monetization.

- There should be harmonization of **measurement, accounting, and emission standards**. Regulations that avoid routine flaring and venting should be the minimum standard. However, many governments do not distinguish routine flaring from total flaring in their data. There is ambiguity in the definitions of 'routine flaring' and 'normal production operations'. As atmospheric emissions and their impacts are border-crossing, there should be harmonization of emission standards and measures across neighbouring states.
- Central banks and major investors are now asking companies to align their reporting with the TCFD's recommendations. Although the social impact of flaring and venting exceeds climate-related damages, the frameworks of the TCFD and OGMP are valuable to improve transparency on these emissions. This increased transparency will further benefit action to also address health and other social impacts from flaring and venting.

8.5 Capturing economic and social value for global health and climate

People living in low- and middle-income countries disproportionately experience the burden of outdoor air pollution, defined by the WHO as particulate matter (PM)—which includes BC, ozone (O_3), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2). These chemicals have a significant role in causing cardiovascular illness and death. Of the 4.2 m premature deaths globally in 2016, 91 per cent occurred in low- and middle-income countries, particularly in the WHO South-East Asia and Western Pacific regions.

By quantifying in US$ terms the total SCAR from flaring and venting, including the harm to human health, our work shows that methane and other non-CO_2 releases contribute 96 per cent of SCAR. Combining individual flare data with the remote sensing of other satellites, such as NASA's Aura satellite, can provide **more accurate rate estimates** and a detailed picture on individual chemical releases that determine flare quality and SCAR. There are also advances in the monitoring of methane emissions with the recent launch of GHGSat's satellite Iris, a much improved version of satellite GHGSat-D Claire. Furthermore, satellite **measurement** of gas flaring in 105 countries enables the social costs of individual flares to be calculated and allows prioritization, i.e. the identification of 'super-emitters'. The ability to **measure individual releases** and establish reliable correlations between releases (such as between NO_2 and BC) enables SCAR estimates that account for both the volume and the quality of natural gas flaring.

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 operational failure of flares to meet emission standards has significant impacts on health and climate, including through vented hydrocarbons and non-methane VOCs. The partial combustion of VOCs and aerial oxidization of VOCs creates chemicals known as 'organic carbon'. Work is progressing on BC, which in addition to its health impacts has also been found to be the strongest contributor to climate change after CO_2, particularly in its impact on the Arctic. Its short lifetime in the atmosphere provides a major opportunity to mitigate climate change.

8.5.1 Regional effects

Calibrating satellite observations with local data can further develop transport models to assess regional distributions of SCAR. This will not only identify the emission locations of the largest contributors to SCAR from venting and flaring; it will also help to establish potential relationships between flaring and venting emissions. For example, assessing flares for methane emissions can point to incomplete combustion and badly operated flares.

Various countries have shown positive results in reducing flaring and fugitive emissions and provide experience others can build on. Eradication of flares and vents ranked by volume emitted (as well as by pollutants) benefits health and climate, and enables the assessment of which flares provide the best financial and **economic returns** from capturing the gas.

About 20 countries include reduction of GHG emissions in their respective NDC targets. Gas capture would exceed NDC targets in Yemen, Algeria, and Iraq and make a substantial contribution in Gabon, Algeria, Venezuela, Iran, and Sudan. Apart from countries with high oil production and an underdeveloped gas economy (Iraq, Iran, Angola, Venezuela, Nigeria), we also see countries like Ghana, Philippines, Chad, Guatemala, and Cameroon with little oil production and few, but high-rate, flares.

Therefore, focused efforts to eradicate sources of flaring and venting provide a significant impact in addressing climate change, while simultaneously contributing to the energy transition in developing countries with local development benefits at a material scale.

8.5.2 Solutions and recommendations

- Given their disproportionately large environmental impact, the occurrence of super-emitter flares should be avoided, and **penalties imposed for not meeting flare quality standards**.
- The integration of satellite data provides higher accuracy on volumes flared and can provide key information on flaring quality. Further work is needed to develop models that calibrate satellite observations with **metered data** and other local emissions data, to enable satellite-based SCAR assessments for individual flares and vents.
- In combination with transport models and other geographical information (such as population density), regional and cross-border distributions of SCAR from local emitters can be assessed and the potential for mitigation, i.e. commercialization of the gas, determined. It is critical that satellite data of atmospheric emissions remain in the public domain and accessible by third parties for **verification** and by the public for **transparency**.
- IEA estimates that around 40 per cent of the 81.5 Mt of methane emissions that occur in global oil and gas operations today could be avoided with measures that would have no net cost. 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.

Table 6 summarizes the economic and social value identified from eradicating flares and vents. The Diamond model provides the combination of tools and levers to implement a gas capture programme that contributes positive value to economics, finance, health, and climate.

Table 6: Overview of the socioeconomic impact of local gas flaring and venting in terms of cost

Opportunity cost	Externality cost

Impact area	Local	National	Global
Energy conservation	Operational energy efficiency lost due to flaring and venting	Energy potential lost due to flaring and venting	Alignment in adoption of standards for responsible development
Energy access	Local energy generation from flare and vent gas	Connecting infrastructure opportunities and market access (CNG, gas grid)	Global replication of technology developed for small-scale gas utilization
Air pollution	Health impact of PM2.5 particulates and toxicity of VOCs, OC, BC, smoke	Health impact of PM2.5 particulates: health care costs and loss of productivity	Air quality benchmark project for global replication
Ground pollution and crop growth	Toxic chemical absorption in the food chain; negative impact of methane on crop growth	Toxic chemical absorption in the food chain; impact on health and agriculture productivity	Toxic chemical absorption in the food chain; impact on health and global food cost
Water pollution	Ground water contamination from solubility of VOCs		
Climate impact	Precipitation impact of atmospheric releases (acid rain)	Precipitation impact of atmospheric releases (weather patterns)	Global warming from atmospheric emissions of methane, CO_2, BC, OC, NO_X, SO_X
Development	Local development opportunities from gas utilization; economic activity from energy access	National (infrastructure) development from gas utilization; country energy efficiency	Global replication of the 'Diamond Programme' to eradicate flaring and venting
Finance	Social licence to operate	Access to capital	Access to markets

Source: authors' illustration.

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Abbreviations and units

ABS	American Bureau of Shipping
APG	associated petroleum gas (= associated natural gas)
bbl	barrel (1 bbl is 0.159 m^3)
BC	black carbon
Bcfd	billion cubic feet per day (1 Bcfd NG = 7.6 Mtpa of LNG)
bcm	billion (= one thousand million) cubic metres
BLM	US Bureau of Land Management
BOEM	US Bureau of Ocean Energy Management
bpd	barrels per day
BSEE	US Federal Bureau of Safety and Environmental Enforcement
CAGR	Compound Annual Growth Rate
CAP	Critical Air Pollutants
Capex	capital expenditure
CCAC	Climate and Clean Air Coalition
CDP	Carbon Disclosure Project
CNG	compressed natural gas
CO_2e	Carbon dioxide equivalent
DFID	UK's Department for International Development
DMSP	Defense Meteorological Satellite Program
EBRD	European Bank for Reconstruction and Development
ECA	Emission Control Area
EDGAR	Emission Database for Global Atmospheric Research
EDF	Environmental Defense Fund
EI	extractive industries
EPA	Environmental Protection Agency (US)
FLNG	Floating LNG (liquefaction facility)
FSB	Financial Stability Board
GGFR	Global Gas Flaring Reduction Partnership, led by World Bank Group
GHG	greenhouse gas, such as carbon dioxide, methane, and others
GMA	Global Methane Alliance
GMI	Global Methane Initiative
GTL	gas-to-liquids (a gas refinery that produces liquid fuels from natural gas)
GTS	Gas Transmission System
HAP	Hazardous Air Pollutants

IEA	International Energy Agency
IMF	International Monetary Fund
IOC	international oil company; most often refers to large international integrated oil and gas company
IMO	International Maritime Organization
IMP	Instituto Mexicano del Petróleo
KMAO	Khanty-Mansiyskiy Autonomous District in Russia
kscf	thousand standard cubic feet
LNG	liquefied natural gas
MGP	Methane Guiding Principles
MMBtu	million British Thermal Units—measure of the energy content in fuel (1 BTU = 1.06 J)
MMscf	million standard cubic feet
MMscfd	million standard cubic feet per day
Mt	megatonne, a unit of mass equal to one billion kilograms (10^9 kg)
$MtCO_2e$	megatonnes of CO_2 equivalent (emissions)
Mtoe	million tonnes of oil equivalent
Mtpa	million tonnes per annum
MW	megawatt—one million watts
MWh	megawatt hour—unit of measure of electric energy
NDC	voluntary Nationally Determined Contributions to limit global warming
NEI	National Emissions Inventory of EPA (US)
NFRD	Non-Financial Reporting Directive
NGFS	Network (of central banks and supervisors) for Greening the Financial System
NG	natural gas
NGO	non-governmental organization
NNPC	Nigerian National Petroleum Corporation
NOAA	National Oceanic and Atmospheric Administration (US)
NOSDRA	National Oil Spill Detection and Response Agency (Nigeria)
NO_x	nitrogen oxides—chemical compounds made from elemental nitrogen and oxygen
OC	organic carbon (partially oxidized VOCs)
OCS	Outer Continental Shelf
OECD	Organisation for Economic Co-operation and Development
OGCI	Oil and Gas Climate Initiative
OGMP	Oil and Gas Methane Partnership
OMI	Ozone Monitoring Instrument (on board NASA's Aura satellite)
OPEC	Organization of the Petroleum Exporting Countries
Opex	operational expenditure

PM	Particulate Matter
PPP	Public–private partnership
SCAR	social cost of atmospheric releases
scf	standard cubic foot
SDGs	Sustainable Development Goals (as defined by the UN)
SENER	Secretaria de Energia de México
SO_x	sulphur oxides—chemical compounds made from elemental sulphur and oxygen
S-NPP	Suomi National Polar-Orbiting Partnership satellite
TCFD	Taskforce on Climate-Related Financial Disclosures
$tCO_2(e)$	tonne of CO_2 (emissions)
tpa	tonnes per annum
tpd	tonnes per day
UNFCCC	United Nations Framework Convention on Climate Change
UNPRI	United Nations Principles for Responsible Investment
VIIRS	Visible Infrared Imaging Ratiometer Suite (onboard S-NPP)
VNF	Identification of night fires by satellite through the combination of VIIRS and visible light detectors
VOC	volatile organic compound
WHO	World Health Organization
WWF	World Wildlife Fund
ZRF	'Zero Routing Flaring' initiative of the World Bank Group

Appendix

A Global gas flares identified from VIIRS satellite data in 2017

Figure A1: Gas flares in Russia and Central Asia

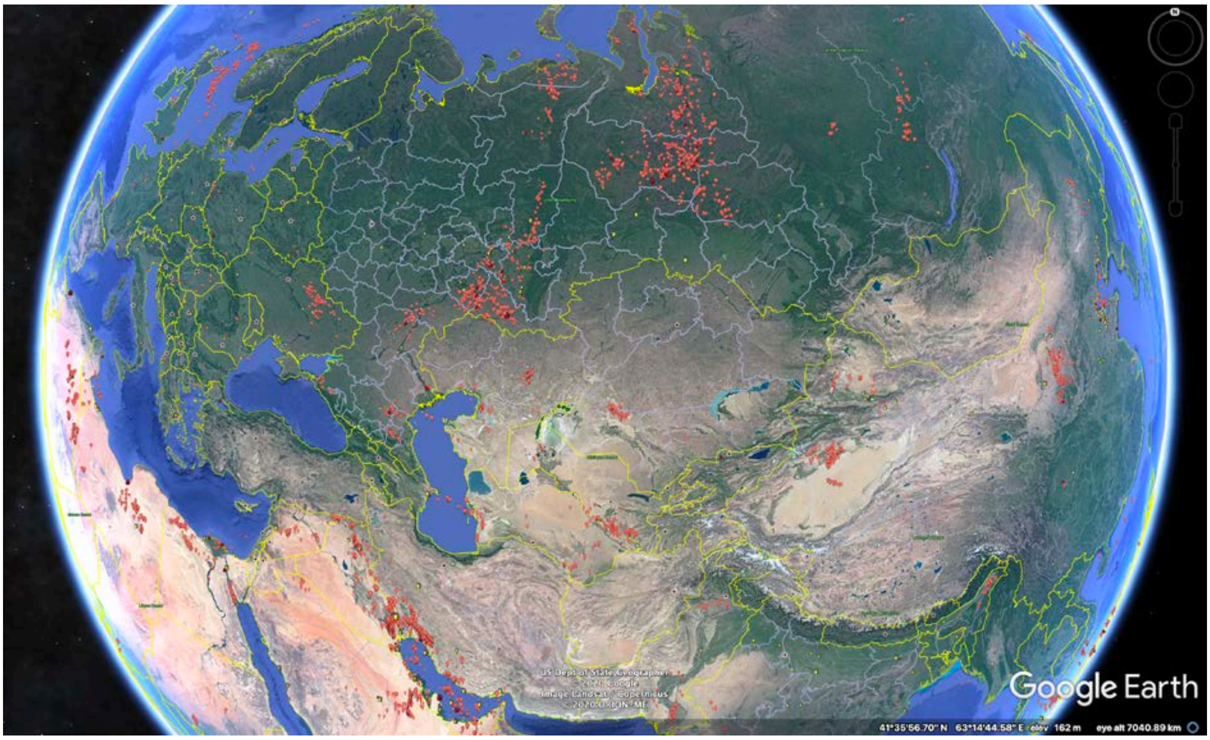


Figure A2: Gas flares in North America

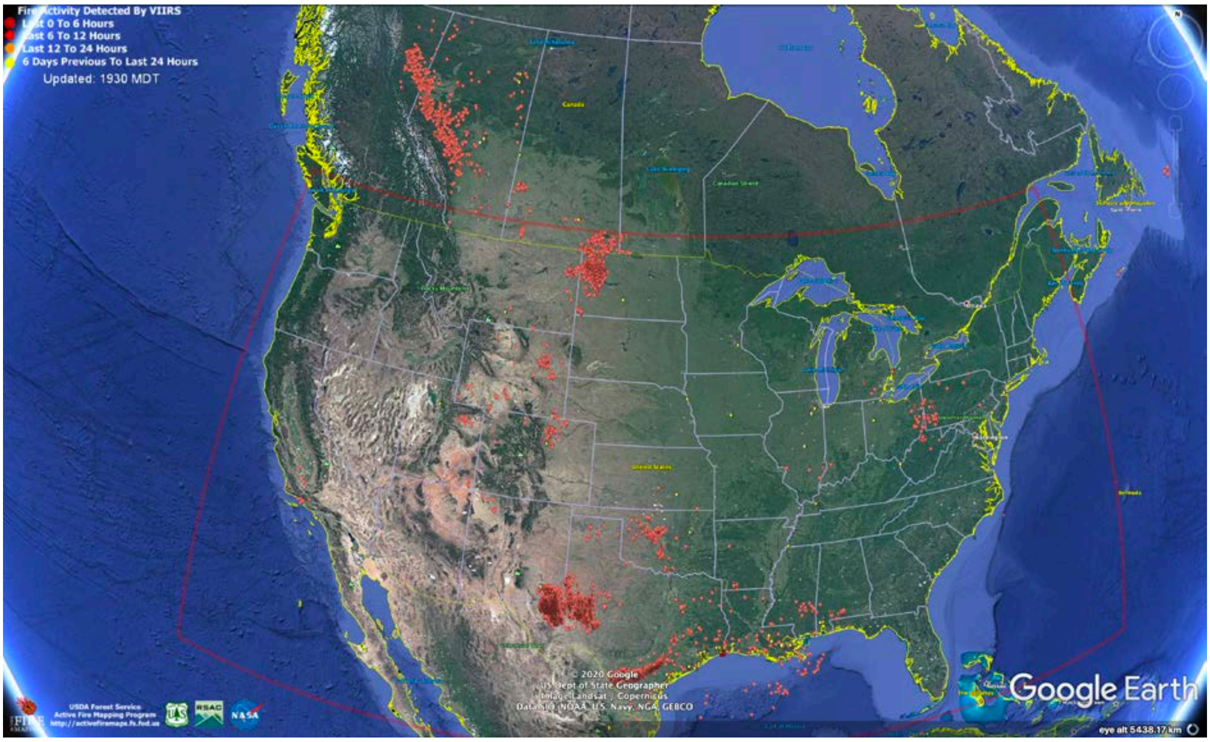


Figure A3: Gas flares in Central and South America

Figure A4: Gas flares in Africa and Middle East

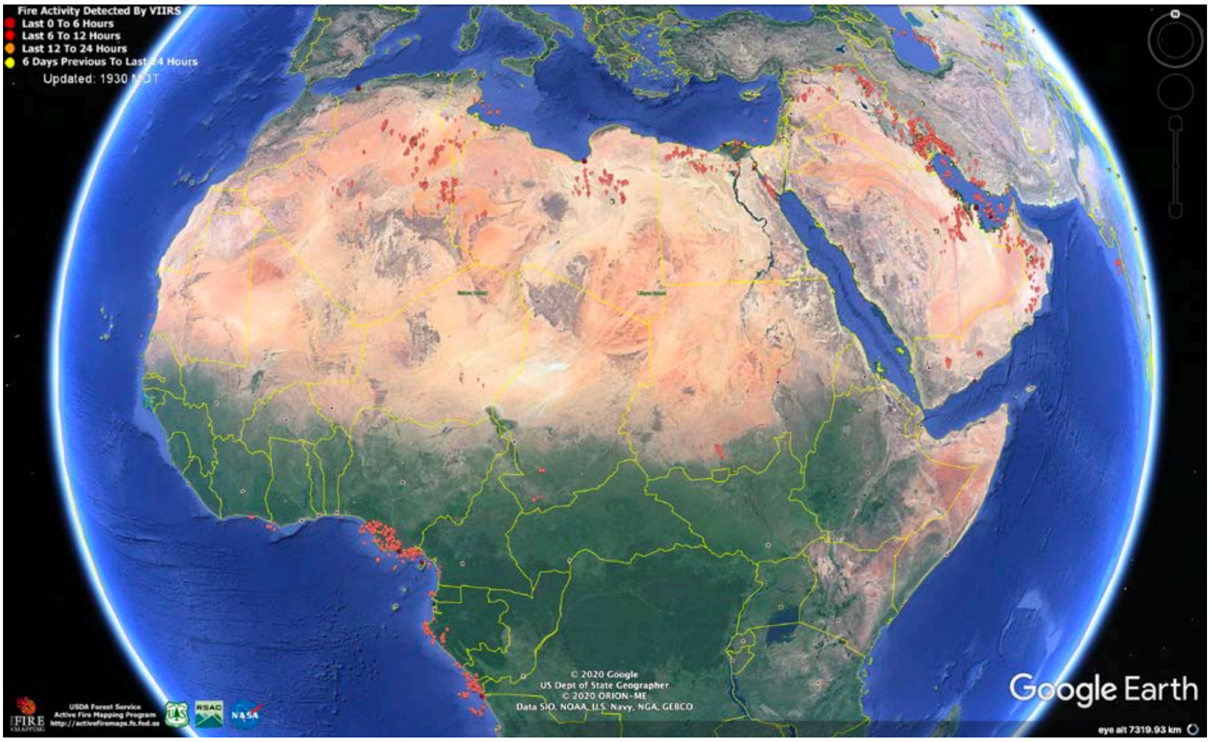


Figure A5: Gas flares in Asia

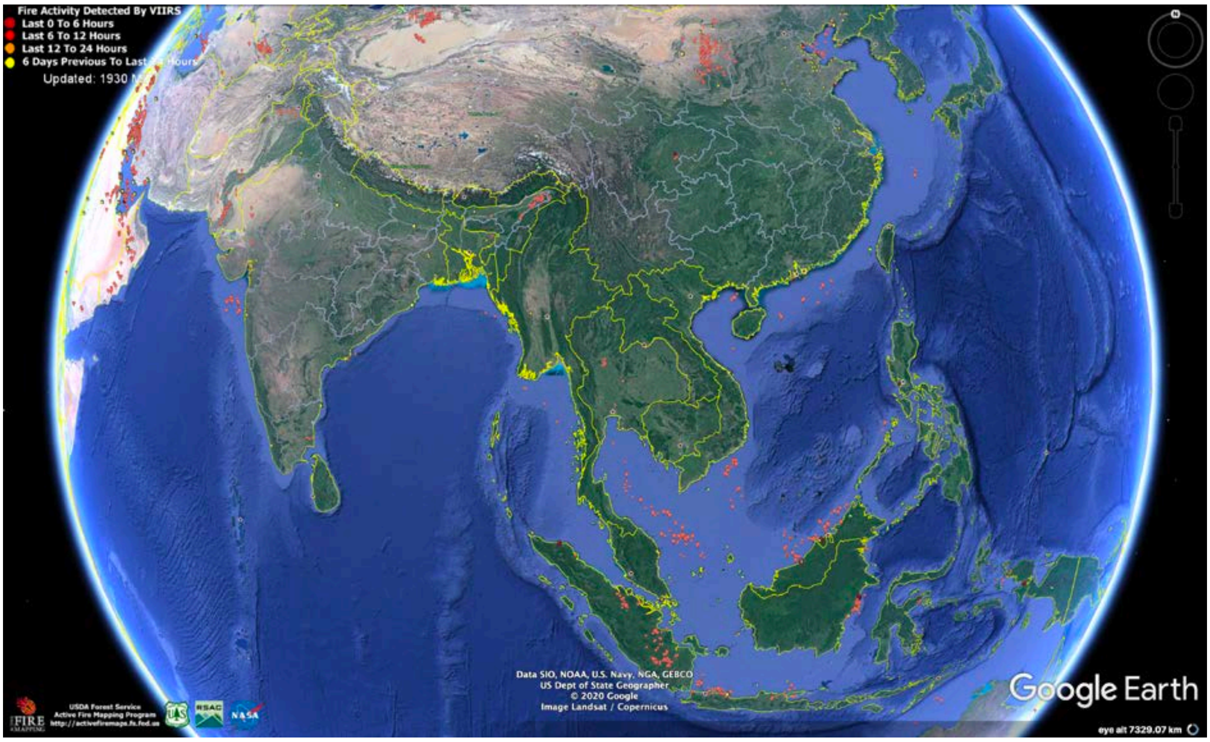


Figure A6: Gas flares in South-East Asia, Australia, and New Zealand

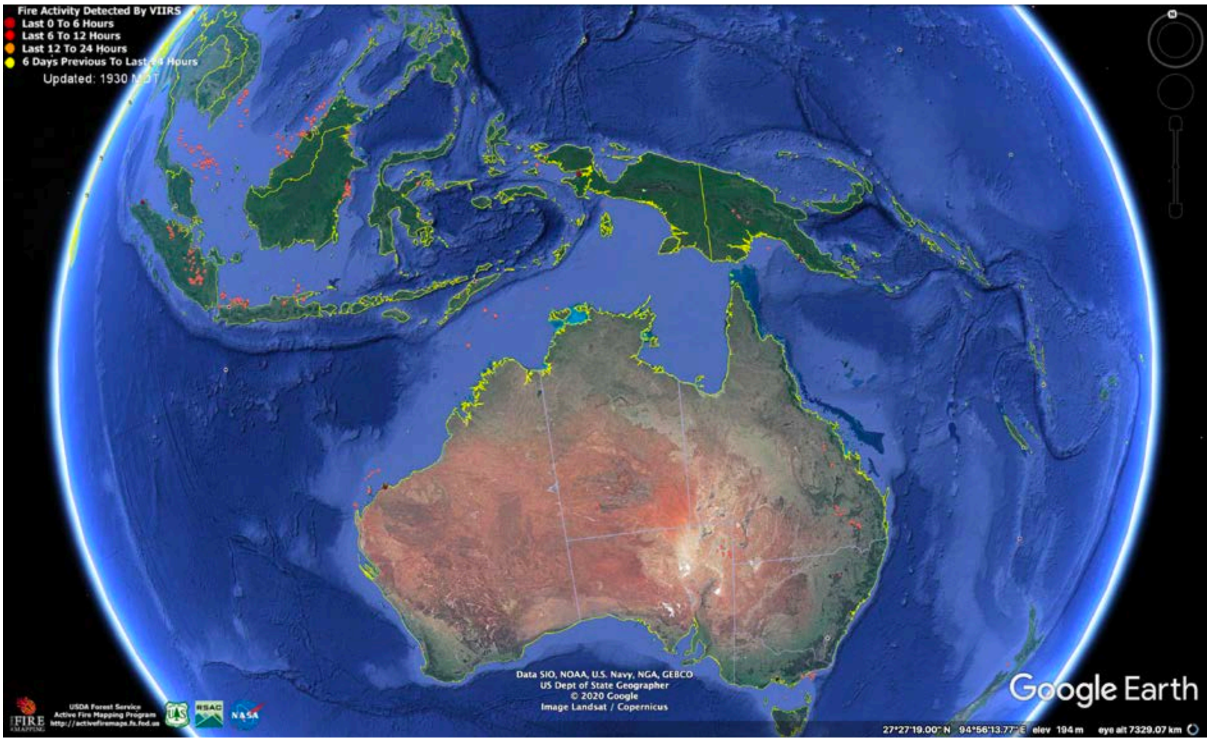


Figure A7: Gas flares in West and East Europe

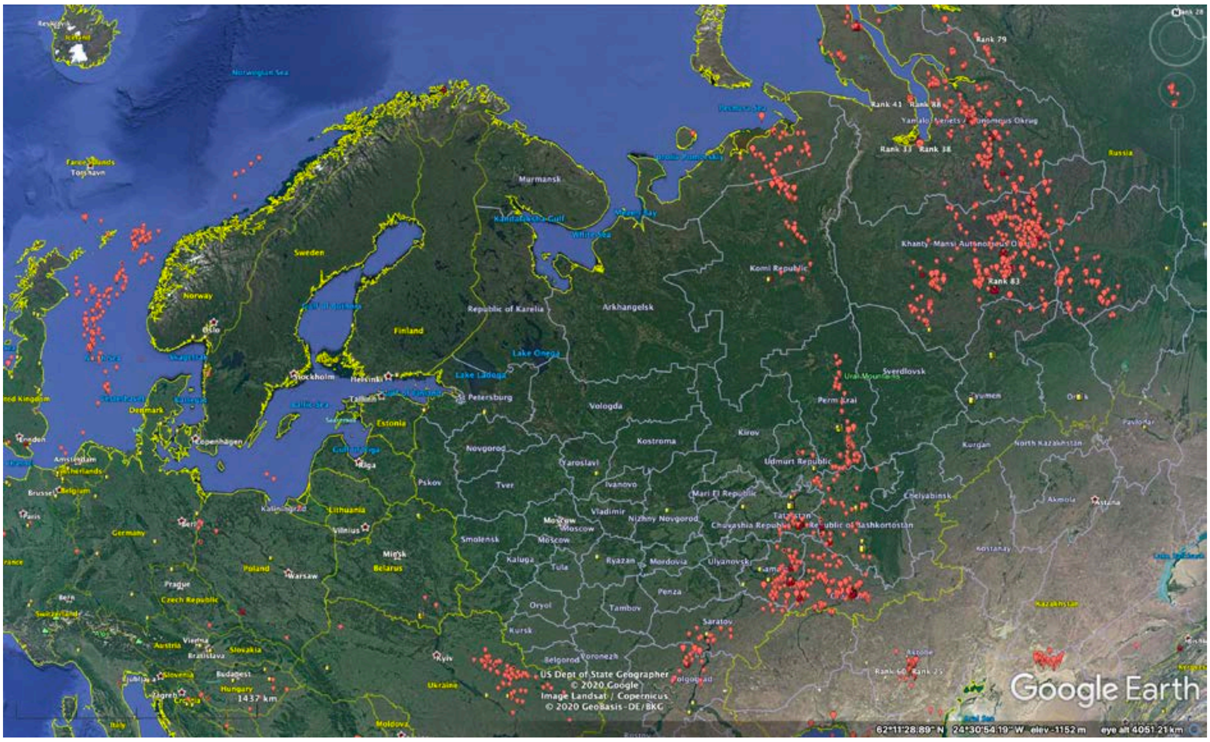
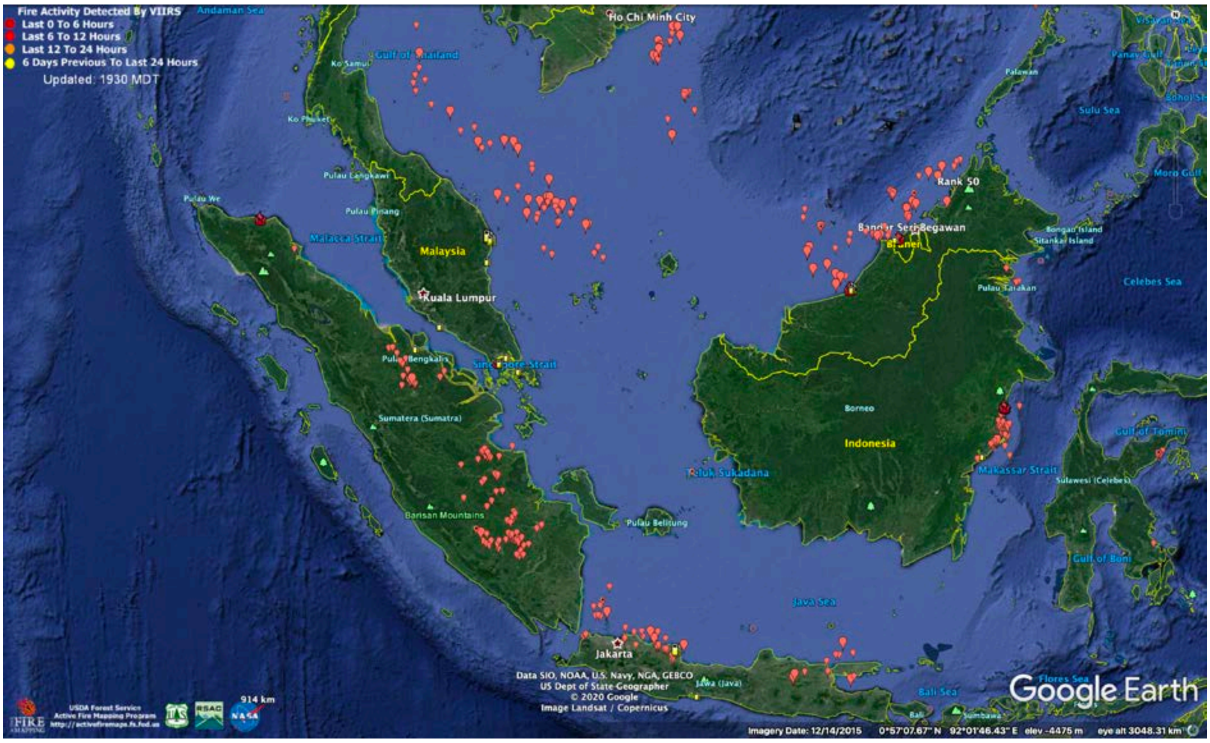


Figure A8: Gas flares in South-East Asia



Source (all figures in Appendix A): authors' illustration based on a combination of Google Earth images with 2017 VIIRS data.

B Countries with policies on climate change, methane, and flaring

Table B1: Countries and number of policies on climate change, methane, and flaring, July 2020

Country/region	Climate change policies	Methane policies	Flaring policies
Canada	28	32	15
Australia	13	27	7
Nigeria	0	16	12
US	7	15	7
Mexico	3	15	5
Norway	9	8	5
Indonesia	0	4	2
Russian Federation	0	4	1
Colombia	0	4	1
Brazil	2	2	3
Argentina	0	4	
Turkmenistan	0	4	
Kazakhstan	0	1	
EU	16		
UK	12		
France	10		
Netherlands	7		
South Africa	6		
Austria	4		
China	4		
Spain	4		
India	3		
New Zealand	3		
Rwanda	2		
Poland	2		
Sweden	2		
Belgium	2		
Germany	2		
Hungary	2		
Moldova	2		
Portugal	2		
Czech Republic	1		
Morocco	1		
Turkey	1		
Scotland	1		
Kiribati	1		
Luxembourg	1		
Finland	1		
Italy	1		
Japan	1		
Total	156	136	58

Source: authors' construction from own calculations based on IEA (undated), 'Policies Database'.