November 2020

Methane Emissions from Natural Gas and LNG Imports:

an increasingly urgent issue for the future of gas in Europe

OIES PAPER: NG 165

Jonathan Stern, Distinguished Research Fellow, OIES

ISBN 978-1-78467-170-9

Acknowledgements

Colleagues at the OIES have been kind enough to read through the text and make helpful suggestions including: Alex Barnes, Mike Fulwood, James Henderson, Anouk Honoré, Martin Lambert, David Ledesma, Simon Pirani and Katja Yafimava. Special thanks are due to Marshall Hall who spent a great deal of his time discussing the subject with me, alerting me to many sources that I otherwise might have missed, filling in gaps in the text, and helping greatly by calculating methane intensity values.

Outside the OIES I am grateful to: Tomas Bredariol, Christian Lelong, Christophe McGlade, Antoine Rostand and Peter Zeniewski for providing me with helpful comments and sources for many aspects of this extremely difficult subject.

Thanks for John Elkins for his editorial suggestions and Kate Teasdale who did everything else with her customary efficiency

I am solely responsible for all and any errors and omissions which remain, and all opinions and interpretations.

Preface

The Natural Gas Programme at OIES has been now been publishing research on the challenges of decarbonisation for the gas industry for more than four years, and the topic is becoming ever more relevant. In particular, the EU continues to lead the way with its target for net zero emissions by 2050 and its creation of strategies to encourage all sectors in the economy to implement radical action to achieve this objective. From a gas industry perspective, the latest strategic document concerns methane emissions, and its implications, as discussed by Jonathan Stern in this paper, are potentially very significant.

As Stern highlights at the very start of the paper, the subject is a very challenging one not only because the data are complex but also because their availability varies widely by country and the interpretation of them is not at all consistent. Nevertheless, the message to the gas industry (and indeed to other suppliers of fossil energy) is very simple and clear – establish a methodology to demonstrate the methane emissions in your value chain and show how you are managing them or we (the EU) will apply a default value and charge you accordingly. Essentially, the EU is forcing the gas industry to confront an issue that has dogged it for some time, namely that although it claims to produce the "cleanest" fossil fuel this assertion is undermined by the fact that it has failed to fully address the well-known, but as yet less than accurately quantified, problem of methane emissions across the gas value chain.

In this important paper Stern outlines the key issues that are now being debated and provides his thoughts on the reaction that is now required from all actors in the gas sector. He provides an overview of the key themes, discusses the issues surrounding the measurement, reporting and verification of methane emissions, looks at the specific emissions associated with the key exporters of gas to Europe and then concludes with the key implications of the new EU Methane Strategy. With this report, he continues his recent work on the challenges being faced by the gas industry in Europe, but importantly he also underlines that this is likely to become a global theme as goals for carbon neutrality are now appearing in a number of non-EU countries, especially in Asia. As a result, this issue cannot be dismissed as a region-specific concern, but should be viewed as another instance of the EU acting as a catalyst for the gas sector to prepare itself for a global energy economy within which decarbonisation is becoming an ever more important theme. As such, we hope that readers find this paper both informative and interesting but also a significant contribution to this increasingly vital debate.

James Henderson
Director, Natural Gas Programme
Oxford Institute for Energy Studies

Contents

Figures

Tables

Executive Summary

The subject of methane emissions is extremely challenging. The data are complex, difficult to understand, disputed and often entirely lacking. In an EU context, increasing GHG reduction targets for 2030 have emphasised the urgency to focus on emissions from all fossil fuels. Pressure is mounting on the natural gas community to reduce methane emissions and this is most urgent in EU countries following the publication of the European Commission's Methane Strategy. Because indigenous EU production has been declining rapidly, there are increasing calls for emissions from imported pipeline gas and LNG to be quantified and based on actual measurements. The EU Methane Strategy promises to be a significant milestone in that process. Companies which are supplying (or intending to supply) natural gas to the EU – the largest global import market for pipeline gas and a very significant market for LNG - would be well advised to pay close attention to how the regulation of methane emissions is unfolding. Those supplying markets outside the EU should note the start of similar corporate initiatives in Asian LNG trade.

The Strategy is the start of a legal/regulatory framework in respect of transparent measurement, reporting and verification (MRV) of emissions based on the Oil and Gas Methane Partnership's voluntary commitments. Legislative proposals will be published in mid-2021 with the intention that they will enter into force in 2024. The eventual aim will be the establishment of methane emission standards for (all fossil energy but with a focus on) natural gas sold within the EU. Should countries which deliver gas to the EU fail to adopt this framework, a default value will be established on which their emissions will be based, and it is assumed this value will be used in respect of any future GHG (carbon and methane) prices or taxes which may be introduced.

Enforcing the MRV framework on non-EU suppliers raises complex and potentially controversial legal issues in relation to WTO rules. However, these measures will *significantly* impact only the countries which in 2019 accounted for more than 95% of EU imports: Norway (where reported emissions data already meet any standard which may be imposed) Russia, Qatar, USA, Nigeria and Algeria. Countries can be expected to push back against the Strategy's proposal of a national methane supply index based on their entire oil and gas industries. They are more likely to agree to the establishment of a methane emissions standard for pipeline and LNG export supply chains, measured and verified from the point of production to the border of the EU. The financial costs of compliance (or non-compliance) will require a negotiation in which governments which own or control exporting companies will need be involved, emphasising the need for diplomacy at EU and member state levels.

The Strategy requires natural gas and LNG exporters and importers – as well as downstream stakeholders – to make an immediate and positive response. Failure to do so could accelerate the demise of natural gas in European energy balances faster than would otherwise have been the case, and shorten the time available for transition to decarbonised gases – specifically hydrogen – using existing natural gas infrastructure. Finally, it is likely that this EU initiative will (and arguably already has) attracted attention from other governments and companies involved in global gas and LNG trade. Natural gas and LNG, if based on MRV requirements similar to those in the EU Methane Strategy, may be able to command premium prices from buyers eager to demonstrate their own GHG reduction credentials to governments, customers and civil society. Where the EU is leading other countries seem certain to follow, and this will result in methane emissions becoming an issue of substantial importance in global gas and LNG trade.

Introduction: accurate measurement of methane emissions from European imports: why the urgency?

In 2015, parties to the Paris Agreement (COP21) agreed to, `..aim to reach global peaking of greenhouse gas emissions as soon as possible…so as to achieve a balance between anthropogenic emissions…in the second half of this century..'.[1] Subsequently, the United Nations characterised the acceleration of climate change as a `planetary emergency'.[2] In early 2020 the European Union proposed that `Union-wide emissions and removals of greenhouse gases regulated in Union law shall be balanced at the latest by 2050, thus reducing emissions to net zero by that date'.[3] This was followed later in the year by a European Commission proposal to set a 2030 greenhouse gas (GHG) reduction target of `at least 55%' including emissions and removals (compared with the previous target of 40%).[4] The European Parliament then recommended that the 2030 reduction target should be increased to 60%.[5] In Autumn 2020, carbon neutrality commitments were announced by governments in major Asian importing countries – Japan (2050), South Korea (2050) and China (2060) – as well as the incoming US Biden Administration (2050). Commitment to net zero targets seems likely to lead to an intensification of international policy discussions around emissions from the production and trade (imports and exports) in all fossil fuels - oil, natural gas and coal.

The energy transition will require a substantial reduction in greenhouse gas (GHG) emissions from the energy sector, particularly for countries in the European Union which individually and as a group have adopted climate neutrality (net zero) targets.[6] Combustion of natural gas produces significantly lower carbon dioxide emissions compared with oil and especially coal, which led to it being designated as a `clean' or `the cleanest' fossil fuel. Over recent years, this view has been questioned because of increasing awareness of methane emissions from the (oil and) natural gas value chains, as methane is a much more powerful GHG than carbon dioxide.

There are major problems of availability, measurement, reporting and verification of methane emissions data. Given the growing importance of reducing greenhouse gas emissions in Europe, emissions must increasingly be measured empirically, rather than estimated from standard emission factors which have been the principal methodology used by the majority of countries in their submissions to the IPCC and UNFCCC.[7] National governments are only required to record domestic emissions but, given rapidly falling natural gas production in EU countries, there is an increasing focus on emissions from imported pipeline gas and LNG.[8] As GHG reduction targets increase in severity, governments will need to be clear on how emissions from imported gas will impact national targets (understanding that governments are currently only responsible for their domestic emissions). Investors and financial institutions are becoming increasingly reluctant to support fossil fuel projects[9], but a minimum requirement will be an accurate and verified footprint of their GHG emissions which will also be needed in relation to current and future carbon/GHG taxes.

The major focus of this paper is on emissions from natural gas *imports from outside the European Union*. However, for importing countries outside the EU with less stringent immediate GHG reduction targets, it will also become increasingly important for governments to obtain more accurate data on natural gas and LNG emissions. The emergence in 2019 of `carbon neutral' LNG deliveries, and a tender for cargos with certified GHG emissions, in Asia are important developments which are also discussed. For gas markets less dependent on imports, the emphasis will be on emissions from domestic gas value chains. However, the EU

---

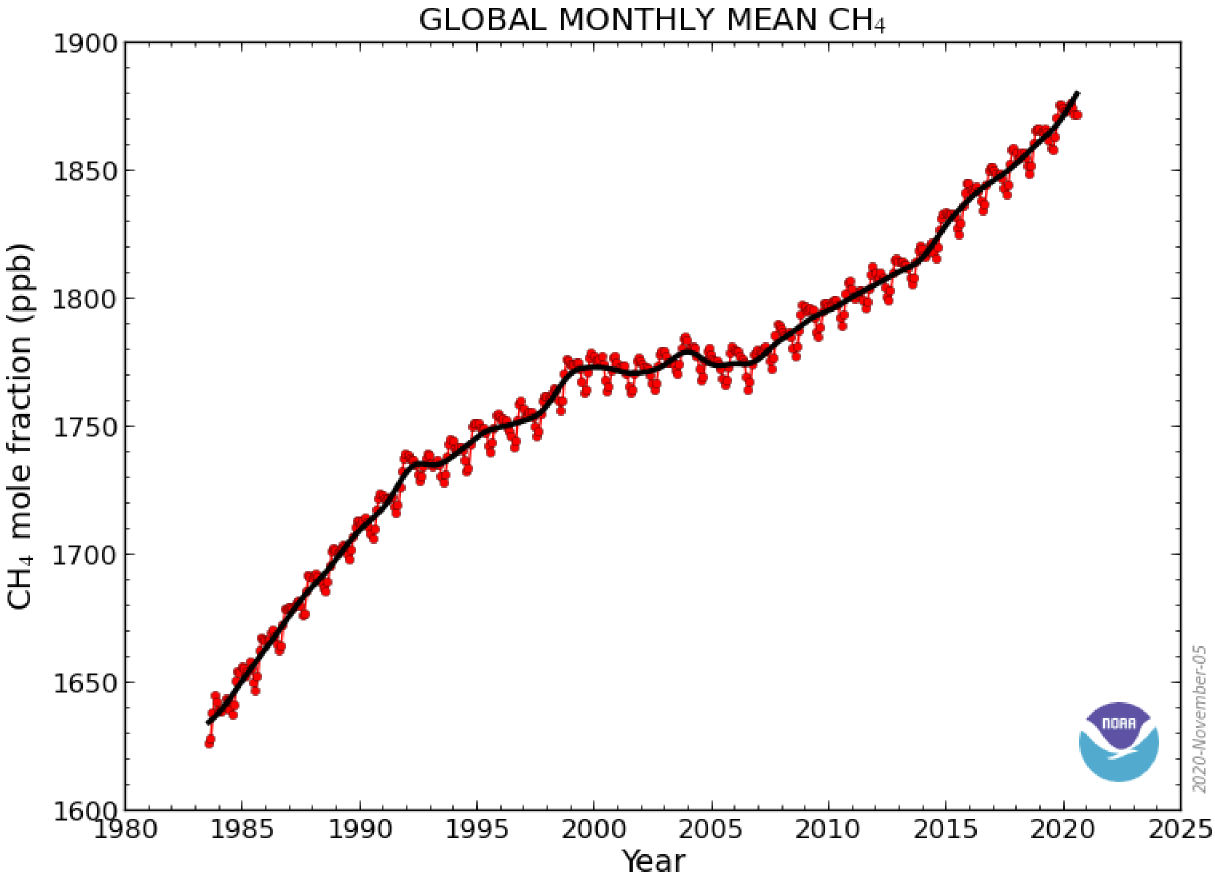
1 UNFCCC (2015), Article 4
2 UNFCCC (2020), Chapter 1, p.5.
3 European Commission (2020a), Article 2(1).
4 European Commission (2020b).
5 European Parliament (2020).
6 The UK left the EU in 2020 but had previously adopted a net zero target for 2050 and therefore many of the observations in this paper may be relevant.
7 Intergovernmental Panel on Climate Change and United Nations Framework Convention on Climate Change.
8 `European' gas production is not falling so quickly because it includes Norway.
9 The European Investment Bank will end funding for all fossil fuel projects at the end of 2021. European investment Bank (2019).

Methane Strategy will require exporting countries to measure, report and verify methane emissions in general, and certainly from pipeline gas and LNG delivered to Europe.

The importance and impact of methane emissions

According to the IPCC's 5th Assessment Report (published in 2014) methane emissions were estimated to account for 16% of global GHG emissions in 2010, using a time horizon of 100 years, having fallen from 18% in 1970 but had increased by 2.7 billion tonnes in absolute terms over 40 years.[10] Figure 1 shows that atmospheric methane levels have risen significantly over the past 40 years, and especially since the late 2000s, with the possibility that by 2020, methane could be accounting for a larger share of total global GHG emissions.

Figure 1: Global Monthly Mean Atmospheric Methane Levels 1980-2020



Source: Dlugokencky (2020).

Measurement of methane emissions and attributing them to specific sources is an extremely complex exercise. For the period 2008-17, around 60% of global emissions were attributed to anthropogenic (human activity) sources of which the most important are: agriculture and waste, fossil fuels and biomass and biofuel

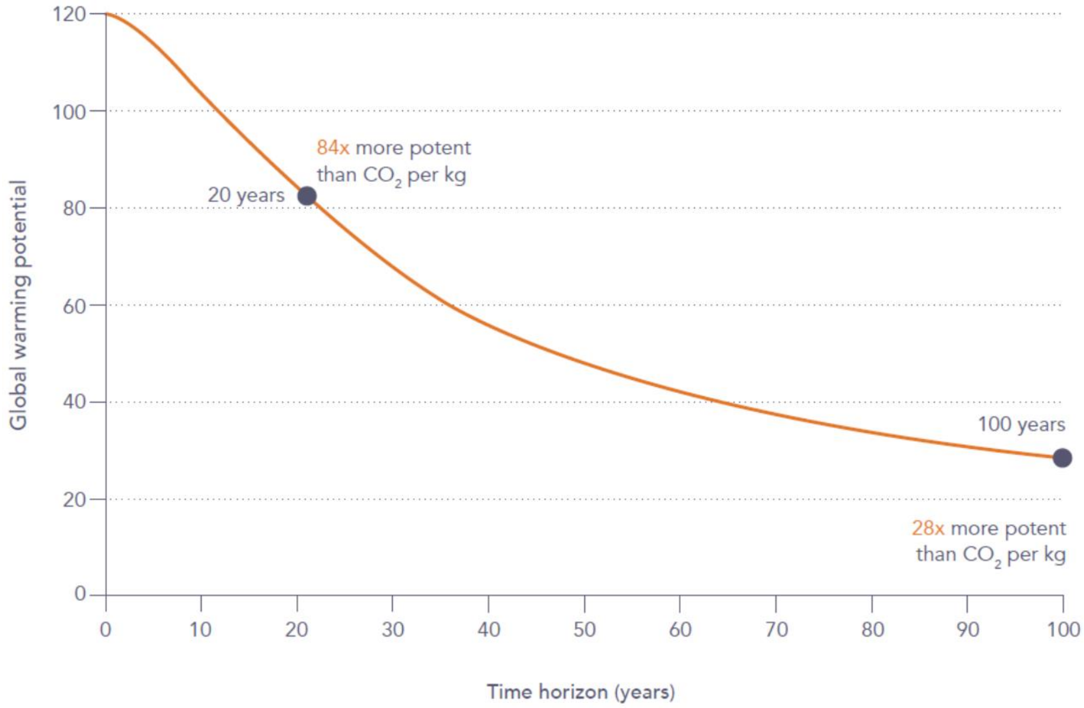
[10] IPCC (2014), pp.6-7. The IEA Methane tracker explains the lifetime issues as follows: `Methane has a much shorter atmospheric lifetime than CO2 (around 12 years compared with centuries for CO2) but it is a much more potent greenhouse gas, absorbing much more energy while it exists in the atmosphere. This means that one tonne of methane can considered to be equivalent to 28 to 36 tonnes of CO2 if looking at its impact over 100 years.'

burning.[11] The remainder are natural emissions of which the most important are wetlands and non-wetland inland waters. 60% of the global increase in anthropogenic emissions from 2000-17, were attributed to agriculture and 40% to fossil fuels, of which 57% were from oil and gas and the rest from coal. The largest increase in fossil fuel emissions was in China, but North America, Africa, South Asia and Oceania were also significant.[12] Fossil fuel related methane emissions in the US accounted for 80% of the increase in North American emissions from 2000-06 to 2017.[13] Europe is the only continent where methane emissions appear to be decreasing, perhaps due to the fall in fossil fuel production.[14] Within the EU, 53% of anthropogenic methane emissions come from agriculture, 26% from waste and 19% from energy.[15]

Interpretations of the global warming potential (GWP) of methane

Methane is a much more powerful greenhouse gas than carbon dioxide. Over a time horizon of 20 years the radiative forcing impact of methane – the global warming potential (GWP) – is estimated at 84-87 times that of carbon dioxide; over a horizon of 100 years estimates range from 28-36 times.[16] These are the two time horizons which have been agreed by the international community within the IPCC assessment process. However, there is no agreement among atmospheric scientists about: which time horizon is most appropriate, how GWP should be translated into a temperature trajectory, and whether GWP or global temperature potential (GTP) is a more appropriate metric.[17]

Figure 2: The Changing Global Warming Potential of Methane over Time



Source: Balcombe et al. (2015), Figure 4, p.15.

---

[11] Saunois et al. (2020), Table 3, which also reveals that using top-down measurement anthropogenic sources accounted for 61% of total methane emissions but using bottom-up measurements only 51%. For more on the difference between top-down and bottom-up measurements see Section 2 below.

[12] Ibid

[13] Jackson et al. (2020).

[14] Ibid.

[15] European Commission (2020c), p.2.

[16] IEA Methane Tracker Website. The IEA uses figures of 85 over 20 years and 30 over 100 years. IEA (2018), Box 11.3, p.490. Balcombe et al. (2015) p.16.

[17] Wang et al. (2013) has a discussion of GWP and GTP metrics and how their selection impacts the emissions of different countries. Allen (2017) shows how reduction in emissions of methane (and other non-CO_2, short-lived pollutants) can have a significant impact on temperature responses.

The IPCC progressively raised the GWP for methane over a 100 year horizon to 28 in Assessment Report (AR) 5 published in 2014.[18] AR6 which is due to be published in 2021 may raise the GWP of methane further.[19] AR5 used a 100 year horizon and noted this was the `..most widely used by governments but we are mindful that other time horizons and other global warming metrics also merit attention'.[20] Figure 2 shows how the GWP of methane changes over different time horizons. Governments will need to take a view on the time horizon and hence the impact on GHG emissions, as they will be entering these values into their national inventory reports and factoring them into their GHG reduction targets. They also need to take a view of sinks for, as well as sources of, methane which is an equally (if not more) complicated and contentious issue.[21] Any decision to adopt a significantly shorter time horizon would substantially increase the importance of methane in GHG inventories and the ability of governments to meet their agreed reduction targets.[22]

This paper is structured as follows: Section 2 examines the methodologies for measuring, reporting and verifying emissions and the available sources of data. Section 3 looks at the different ways of calculating the intensity of methane emissions from the countries which export gas and LNG to the EU, and some new developments in Asia. Section 4 reviews the EU's Methane Strategy, published in October 2020, which promises to significantly increase the importance of methane emissions from all sources, but particularly natural gas imported into EU countries. The final section summarises and concludes.

2. Measuring Methane Emissions: methodologies and data sources

There are three main categories of methane emissions from (oil and) natural gas operations:

- venting from oil and gas production and processing sites (venting tends to be deliberate rather than accidental or fugitive);
- flaring which is mainly CO_2 but can include methane and other hydrocarbons which have not been completely combusted particularly from gas associated with oil production but also dry gas production sites;
- fugitive methane emissions (usually unintended leakage) from natural gas transmission and distribution operations, including long distance pipelines for import and export of natural gas; and the liquefaction, shipping and regasification operations of LNG trade.

For an illustration of where these categories of emissions occur in different parts of the natural gas value chain see Appendix 1.

This paper is principally concerned with emissions from the natural gas sector, but also from the oil sector where natural gas is co-produced. It is not principally concerned with coal although the latter is a major source of methane emissions and is important because of claims that coal to gas switching can substantially reduce GHG emissions (see Section 3). The IEA estimated 2018 methane emissions from the oil and gas sector at 80mt and coal mine methane emissions at 40mt.[23] Estimates of coal emissions are very complicated and vary significantly depending on the type of mine, the depth of operations and the specific country.[24]

---

[18] IPCC (2014), Box TS.5, p.47. However, this recommendation does not yet seem to have been universally adopted and some governments may still be using a GWP of 25 to report their emissions.
[19] There are suggestions that, in order to adequately reflect climate change feedbacks, the GWP factor would need to be raised to 36.
[20] IPCC (2014), p.125.
[21] For a review of sinks see Kirschke et al (2013).
[22] Unless otherwise stated, and taking into account that not all sources cited in the paper are clear about their assumptions, all methane emissions data in this paper stated in CO_2 equivalent – or CO_2-eq - have been calculated using a 100 year time horizon and a factor of 28 x CO_2. The IEA calculate methane emissions data using a GWP of 30.
[23] IEA (2019a), p.245 and 248.
[24] Ibid pp. 245-251 has a review of these factors.

Top down and bottom up measurement methods[25]

Emissions are measured using bottom-up (ground level) and top-down (aerial) methods.

“Bottom-up” calculations estimate emissions from a representative sample of ground level devices. They calculate emissions based on activity factors and emission factors, i.e. number of gas production sites (the activity factor) multiplied by average annual methane emissions per location, process or piece of equipment (the emissions factor). This is a source-specific quantification approach where emissions from each identified source are individually calculated.[26]

“Top-down” calculations are carried out on a regional scale using aerial methods, and measure methane concentrations in ambient air and calculate methane flux as a function of meteorological conditions.[27] Top-down studies mainly rely on aircraft flying upwind and downwind of a study area but are also increasingly using satellite data (see below). Each method has advantages, disadvantages and uncertainty factors which mean that without temporal and spatial reconciliation, each can produce a different (and often substantially different) result for the same region.

Drones are an increasingly common method of identifying and estimating emissions from (oil and) gas operations but it is not clear how they fit into these typologies. While they are certainly aerial (and therefore top-down) measurements, they are focused on specific sites (which could therefore be considered bottom-up) and may not be sufficiently elevated to fully capture emissions from flaring and venting.

Critics of the bottom-up method cite the following flaws in the methodology:

- Inaccurate data leading to under-reporting – because it is source-specific, every single source must be taken into account. Sources may have been missed or under-counted, and activity factors can be out of date, incorrect or understated. Further, emissions factors can also be out of date, incorrect, or inaccurate.
- Bottom-up methodologies may not fully capture all of the sources, which are captured in top-down.
- Component-based studies can under-sample abnormal operating conditions such as malfunctions and large leaks. “Super-emitters” (see below) are not included, as average emission factors do not account for high emitting sites.

Criticisms of the top-down method include:

- Temporal issues – because estimates are generally based on only one or two measurements from flights of limited duration (hours), or when satellites are passing overhead (every few days), the data may not represent average emission rates over a longer time span. For example, in a National Academy of Science study, the key source explaining the difference between top-down and bottom-up estimates was manual liquids unloading, where emissions usually occur during daytime operator shifts, which is also when meteorological conditions were ideal for aircraft methane emission measurements.[28]

---

[25] Some of this section is taken from: Gaffney Cline (2020). For additional accounts of bottom-up versus top-down methodology see Balcombe et al (2017) and IEA (2017), pp. 403-4.

[26] The best practice guides on the Methane Guiding Principles website https://methaneguidingprinciples.org/best-practice-guides/ contain considerable detail on the different methods, in particular the *Identification, Detection, Measurement and Quantification Guide* (2020).

[27] GIE and Marcogaz (2019), p.138 has the following definition: An estimate made using different ‘aerial-based’ techniques to measure ambient air concentrations of methane, calculate methane flux based on atmospheric and meteorological conditions, and then attribute the emission portion due to different activities. Each measurement technique has different resolution capabilities, strengths and weaknesses. Methane emissions are allocated to the natural gas industry by: (a) using a ratio of methane to ethane or propane (longer chain aliphatics which do not occur from biogenic sources); (b) isotopic ratio analysis, using a co-located tracer (such as SF6 or C_2H_2); or (c) subtracting estimates of other sources of methane emissions such as, livestock, wetlands, agriculture, waste management, etc. together with background methane concentrations.

[28] National Academy of Sciences (2018). Liquids unloading is a process by which liquids are removed from more mature wells in order to maintain gas flow. Balcombe et al. (2015), pp.10-11.

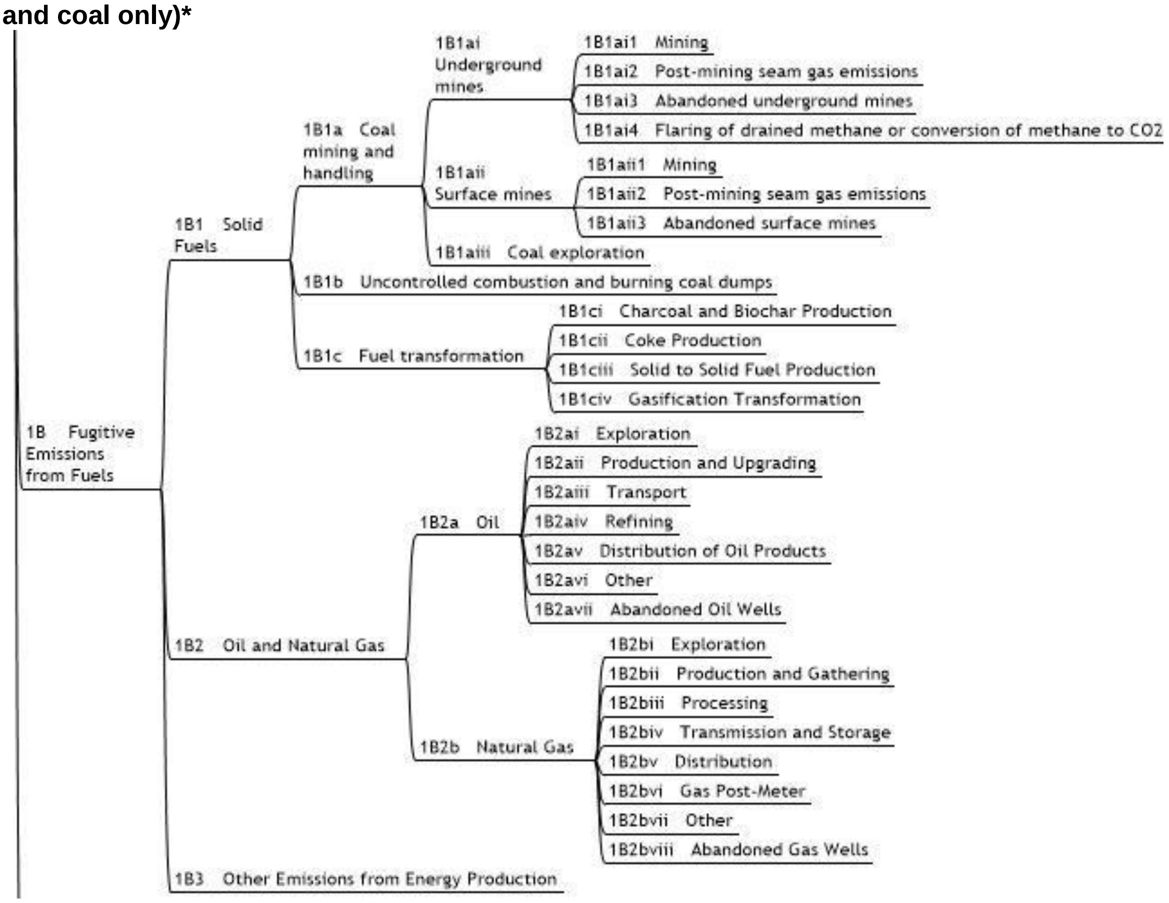
- Attribution of top-down measurements of emissions to a specific source is problematic in terms of determining whether the emissions are from agriculture, landfills, or hydrocarbon production. It is claimed that satellites to be launched over the next several years (see below) will be able to differentiate between these methane sources based on isotopic signatures.
- Atmospheric conditions and the presence of aerosols can distort results and lead to uncertainty.
- Satellites are unable to identify methane emissions from some surface conditions (see below).

Neither top-down nor bottom-up estimates can be regarded as "correct." However, if they are reconciled for location and time using facility-specific operational data, the ultimate result is as accurate as possible with current technology.

UNFCCC/IPCC data on methane emissions

The principal source of methane emission data is the UN Framework Convention for Climate Change (UNFCCC) which came into effect in 1994. The 43 Annex 1 signatories to the treaty submit an annual National Inventory Report (NIR) with data on emissions and removals for all GHGs in accordance with guidelines on methodology set out by the Intergovernmental Panel on Climate Change (IPCC). The IPCC established a set of Guidelines for national greenhouse gas emissions inventories in 2006 and updated these guidelines in 2019.[29]

Figure 3: Fugitive Emissions from Energy Activity and Source Structure in the Energy Sector (oil, gas and coal only)*



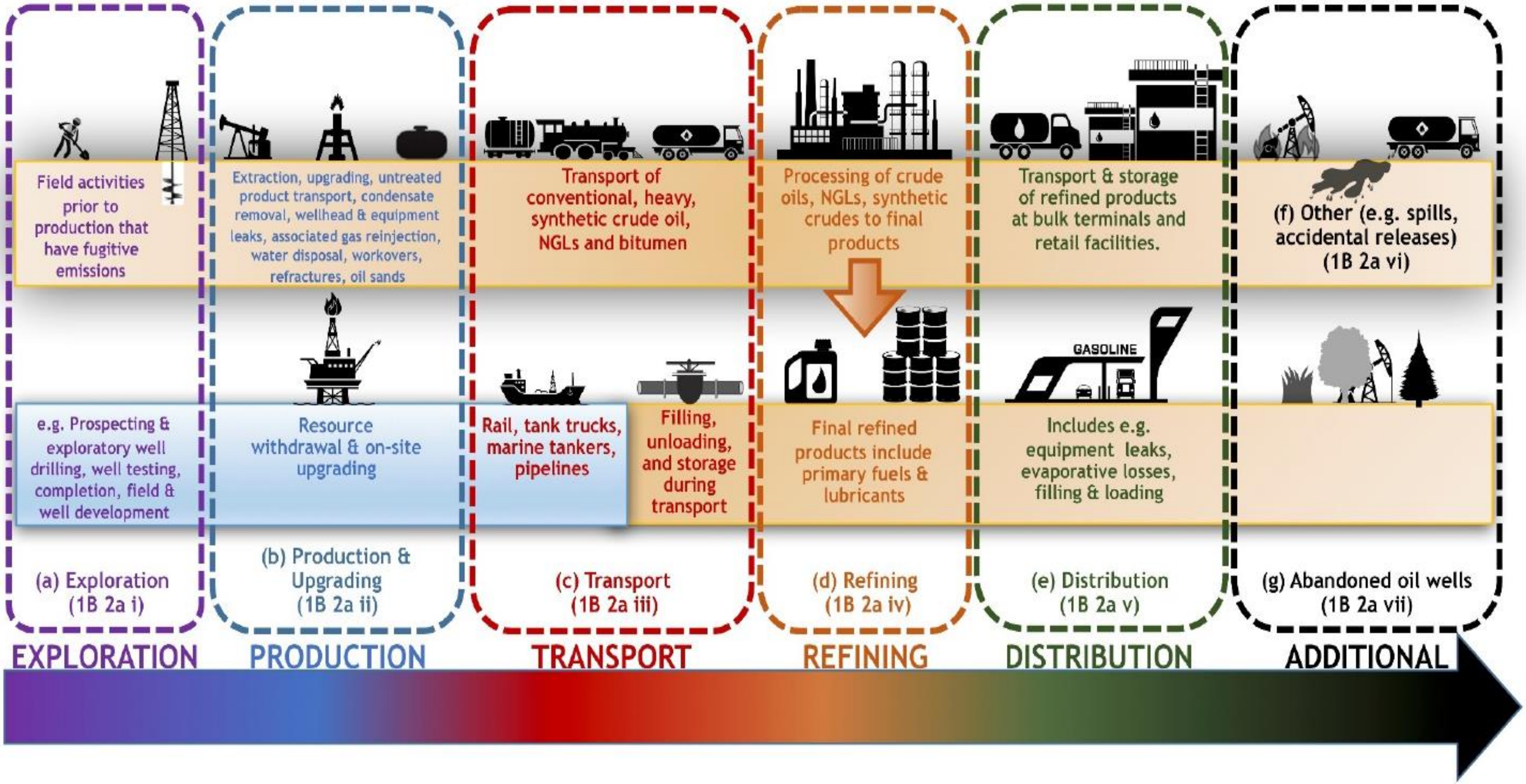
*These are only the sources of fugitive emissions. The original source also includes fuel combustion emissions.
Source: IPCC (2019), Chapter 1, Figure 1.1, p.1.5

[29] IPCC (2006) and IPCC (2019). However, the 2019 Guidelines have not yet been accepted by the Conference of Parties and therefore may not have been implemented by all parties.

Figure 3 shows the extensive classification system by sector and activity established by the IPCC for reporting of fugitive (non-combustion) methane and other GHG emissions from the energy sector. This highlights the need for separation of oil from natural gas activities, and the importance and detail of coal activities. Figure 3 is a very comprehensive classification of fugitive emissions. In practice governments tend to interpret these elements in very different ways, with reported emissions being far less detailed than the figure suggests.

Figure 4 shows the key segments for the natural gas value chain (taken from Figure 3) which go beyond the traditional gas value chain of exploration to distribution. Importantly, these include emissions from gas utilisation at the point of consumption or the `post-meter' segment which are extremely difficult to accurately measure and usually excluded from value chain considerations. The final column marked `additional' refers to `super-emitters' which are discussed below

Figure 4: Key Segments Included in Natural Gas Systems



Source: IPCC (2019), Volume 2, Chapter 4. Figure 4.2.0. p.4.37.

The IPCC Tiers of Measurement[30]

The 2006 IPCC Guidelines for national GHG inventories include three Tiers of measurement. Tier 1 assessments are fuel-based, estimated on the basis of the quantities of fuel combusted multiplied by average emission factors. Tier 2 emissions are estimated from statistics similar to Tier 1, but country-specific emission factors are used in place of the Tier 1 defaults. Tier 3 methods are from detailed emissions models or measurements and data at individual plant level. The IPCC updated the Guidelines in 2019[31] and recognised the limitations of the accuracy of Tier 1 emissions, specifically: `A Tier 1 approach is the simplest method to apply but is susceptible to substantial uncertainties and may easily be in error by an order of magnitude or more'.[32] In relation to Tier 3, the Guidelines commented that, `The application of rigorous bottom-up approaches requires expert knowledge and detailed data that may be difficult and costly to obtain'.[33] The 2019 Guidelines say little about (and may have been agreed before) aerial – especially satellite – monitoring became a recognised and more common methodology.

The IPCC has developed emission values and uncertainty factors for all major greenhouse gases in each of the different elements of each segment of the gas value chain. Detailed IPCC data for methane emission values and uncertainty factors from natural gas exploration, production and processing, for transmission and storage, LNG import and export, distribution and post-meter are shown in Appendix 3. An important consideration is the extent to which the values in these tables, which are mainly taken from US sources, can be generalised across other countries.[34] Two features of these tables are particularly striking:

- emission values for different categories of the same segment of the value chain can be substantially different;
- uncertainty levels for the emission values are commonly +/-20% and can be up to +120% in the distribution and post-meter segments.

Most of the comparable values for oil exploration and production (in Appendix 4) are significantly lower (particularly for exploration) but the uncertainty factors are generally higher at +/-30% rising to +/-50% for transportation. This is an important consideration for gas value chains which include significant volumes of associated gas. Emissions from coal mining (Appendix 5) are complicated by the differences between underground and surface mining; and also emissions from post-mining and drained methane emissions.[35] Uncertainty factors for Tiers 1 and 2 underground and post mining are very large – from plus or minus 50-75% to a factor of 2 greater or smaller, and from plus or minus 50% to a factor of 3 greater or smaller respectively.

The data in Appendices 3-5, based on standard factors with associated uncertainty levels, were a major advance in emission estimates when they were created, and continue to provide a baseline for measurement. But advances in both bottom-up and top-down technologies allow more accurate measurement, and more demanding greenhouse gas reduction targets require much greater specificity and accuracy.

UNFCCC data from national inventories

All Annex 1 countries are required to provide data on national GHG emissions to the UNFCCC which comprise their national inventories (NIRs).[36] The NIRs are long and complex documents and report emissions in different ways. The UNFCCC records GHG emissions from these inventories in a monumental database

---

[30] For detailed definitions of the Tiers see Appendix 2.

[31] IPCC approved these Guidelines in May 2019, but they have not yet been incorporated into the UNFCCC reporting guidelines for GHG inventories. As a result, some countries may still be using the 2006 Guidelines.

[32] IPCC (2019), p.4.39.

[33] IPCC (2006), p.4.36.

[34] All the values for exploration, processing and transmission and storage, and the majority of production values are taken from the US Environment Protection Agency (EPA).

[35] Some of the relevant data for the major categories can be found in Appendix 5, Uncertainty factors tend to be higher than for oil and gas, and depend on whether the methane is vented, flared or collected and used.

[36] National inventory submissions for years going back to 2003 can be found at https://unfccc.int/ghg-inventories-annex-i-parties/2020

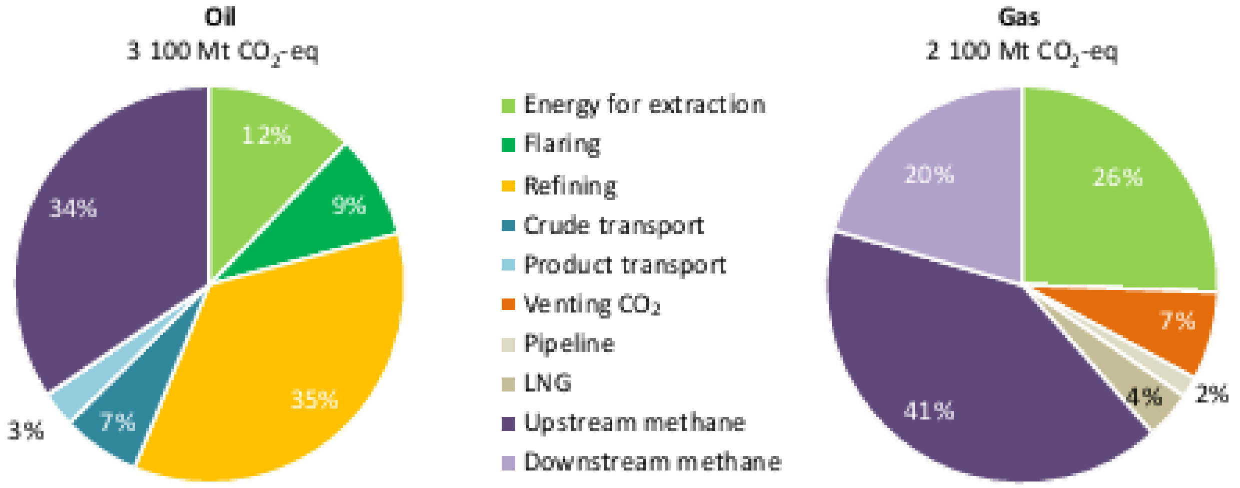
(which can be accessed online) with time series data stretching back to 1990.[37] The data comprise nine modules with detailed data by country and by sector, comparisons by gas as well as fuel categories.

The long-established UNFCCC database has the advantage of temporal consistency but non-Annex 1 countries, including many large oil and gas exporters, do not report as frequently or to the same standard. Even among Annex 1 countries, the standards of reporting and the methodologies adopted vary considerably and there is an evident lack of consistency in the use of the IPCC's sectoral classification of emissions. Submitted data are sometimes also subject to sizeable revision through 'recalculation' as national authorities adopt new emission factors or new reporting methodologies.[38] The perceived quality and accuracy of UNFCCC data for emissions of methane in particular, has suffered as a result of this wide variation of reporting practices.

The International Energy Agency's Methane Tracker

In 2019, the IEA launched its Methane Tracker in response to some of the perceived deficiencies of existing sources. Its scope extends beyond Annex 1 to include most oil and gas producers. The published estimates are based on a variety of industry-based estimates, not on direct country submissions. The published data are presented in 18 categories by activity in upstream and downstream oil and gas. At present, the Methane Tracker has published emission estimates for only two years, 2017 and 2019. The Tracker generates country-specific and production type-specific emission intensities that are applied to production and consumption data on a country-by-country basis.[39] The Agency's methane emissions model takes the 2017 US Greenhouse Gas Inventory, `along with a range of other data sources including our survey of companies and countries…The US emissions intensities are then scaled to provide emission intensities in all other countries'.[40] The advantage of the Methane Tracker is that the data are compiled on a consistent basis although some of the assumptions on which they are based can be questioned.

Figure 5: Breakdown of Global GHG Emissions from Oil and Gas by Element, 2017



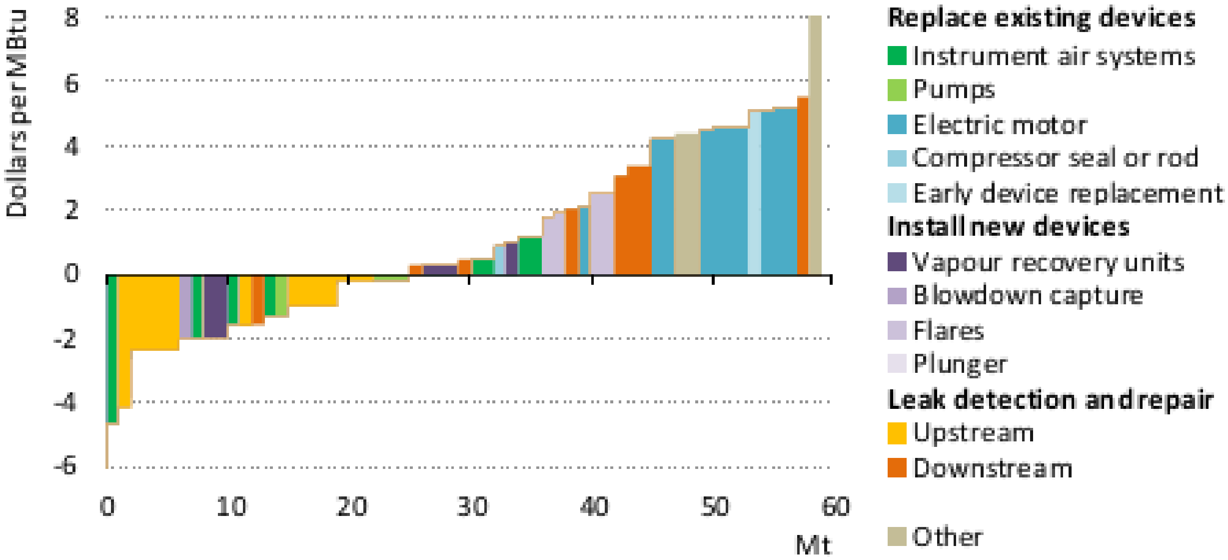
Source: IEA (2018), Figure 11.8, p.491.

[37] https://unfccc.int/process-and-meetings/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc/ghg-data-from-unfccc
[38] For example there was a major reduction in methane emissions reported by the Russian Federation for the year 2013 between the 2015 and 2020 National Inventory Reports which is assumed to have resulted from the change in classifications from the 2006 Guidelines, which divided fugitive emission factors into developed and developing countries and countries with economies in transition (IPCC (2006), Table 4.24, pp.4.48-4.62), and the 2019 Guidelines which eliminated this division (IPCC (2019)).
[39] IEA Methane Tracker Website. The website contains a substantial amount of information including: abatement options, a policy and regulation database, country and regional estimates, and commentary on the quality of the data and how these can be improved.
[40] The countries cover 95% of global oil and gas production). IEA (2020a), pp.63-4. Appendix 7 contains the tables for the US categories of emission sources and intensities and the scaling factors for each country.

Figure 5 shows that 74% of emissions from the gas sector are from extraction, upstream methane and venting CO_2, while 43% of oil emissions are from upstream methane and flaring.

The Methane Tracker analysis also provides costs of abatement for mitigation measures and regions and these are shown in Figures 6 and 7. This data and the methodology on which it is based are extremely important as the figures and the conclusions are universally used in methane emissions literature and by policy makers.[41] The Tracker separates the emission intensities into 86 equipment-specific emissions sources.[42]

Figure 6: Abatement Costs for Oil and Gas Methane Emissions by Device and Process, 2019



Source: IEA (2020b), Figure 2.29, p.89.

The IEA estimates that if all options were to be deployed this would avoid 75% of these emissions and furthermore that around 40% of current methane emissions could be avoided at no net cost since the methane that is recovered can often be sold.[43] Figure 6 suggests that upstream leak detection and repair (LDAR) provide the majority of the emissions which could be avoided at negative cost. Figure 7 shows that the majority of the negative cost emissions are in Asia-Pacific and Africa.

The Agency uses implied wellhead prices to determine the value of the gas captured in each country, but a significant number of assumptions are involved in the calculations.[44] It is clear that year to year changes in import prices (such as the major changes during 2018-20), as well as costs and taxes, will impact the value of methane emissions. Nevertheless, the generalisation that a significant fraction of methane emissions – although difficult to determine exactly – can be captured at negative cost is valid. This may apply particularly to super-emitters unless these are in remote locations which are not connected to national or international networks.

---

[41] For example European Commission (2020c), p.9.

[42] IEA (2020a), p.65 and Appendix 7. This is largely based on US sources with modifications. The specific costs and applicability factors are not disclosed because they are based on proprietary information from ICF. Some publicly available information is available in ICF (2016a) and ICF (2016b).

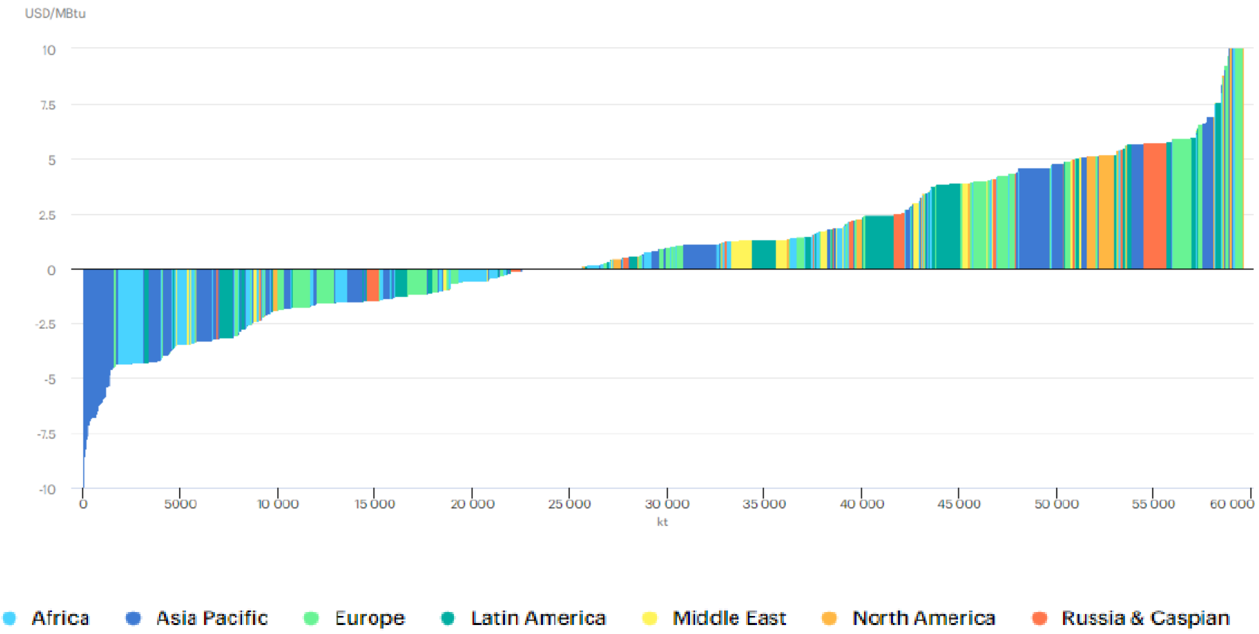
[43] IEA Methane Tracker Website. A slightly higher estimate – 45% of the 82mt of methane emitted – can be found in the Agency's June 2020 tracking report https://www.iea.org/reports/methane-emissions-from-oil-and-gas

[44] `Natural gas import prices are the starting point for the implied well-head prices within each country. To estimate well-head prices over time, each country is assigned to be either an importer or an exporter based on the trends seen in the Stated Policies Scenario. For importing countries, any gas that would be saved from avoiding leaks would displace imports. The well-head price is therefore taken as the import price minus the cost of local transport and various taxes that may be levied (assumed to be around 15% of the import price). For exporting countries, the relevant well-head price is taken as the import price in their largest export market net-backed to the emissions source.' IEA (2020a), p.68.

The IEA is very clear that:

> `The estimates shown represent our best understanding of emissions from oil and gas operations based on currently available data. They are designed to help governments and other stakeholders understand the magnitude of the issue, but given the uncertainty that exists, they are clearly not the last word.'[45]

Figure 7: Marginal abatement cost curve for oil- and gas-related methane emissions globally



Source: https://www.iea.org/reports/methane-tracker-2020

The Tracker updates data for countries where new information becomes available and can therefore act as a kind of `provocation' to governments and companies which consider that the Tracker is overstating their emissions, to demonstrate this through detailed reporting of measurement methodologies and data, even though they have no obligation to report emissions other than to the UNFCCC. The Tracker used Norway as a case study and reduced its estimates of emissions, showing that regulators had worked with operators to provide both general and facility-specific quantification of emissions, which are then used to calculate the taxes paid by operators.[46]

NGO and Academic Studies of Methane Emissions

Most studies published by NGOs and academic researchers use US oil and gas data as the most detailed and openly available source, some of it being empirically observed or modeled from limited empirical datasets. The most complete studies of the methane emissions literature up to the middle of the 2010s are Balcombe et al (2015) and (2017) who note that `the vast majority of the data was from the US, principally data from bottom-up observations and emission factors from EPA'.[47]

Some studies then generalize these data across value chains in both the US and globally.[48] US-focused top-down studies of (mainly) shale oil and gas production generally estimate that emissions in an oil and gas

[45] https://www.iea.org/reports/methane-tracker-2020/improving-methane-data#abstract
[46] Ibid. For a review of these taxes see Hall (2020), p.13.
[47] These studies are based on a review of 454 published papers of which 250 were selected for full review. The authors note that `The papers were collected from a broad range of institutions and were highly variable with respect to data granularity and method'.
[48] For example Nace et al. (2019) in relation to LNG, which uses emission factors from Alvarez et al. (2018). See also Abrahams et al. (2015). For US studies using both top-down and bottom-up methodology, see IEA (2017, 403–13). Howarth (2019) suggests that North

producing region can be much higher than estimates based on bottom-up inventories of hydrocarbons. This has been particularly the case in the Permian Basin where satellite monitoring has shown substantial methane concentrations which have been attributed to flaring and venting.[49] Satellite data shows that flaring and venting from (principally) oil developments in the Permian Basin has produced estimates which are more than a factor of two higher than those derived from EPA data, and significant emissions which will continue until pipeline infrastructure is sufficient for collection and evacuation.[50]

There is debate as to whether the official EPA GHG inventory may have under-estimated methane emissions and this is important because so much of the published (and publicly available) data is derived from this source.[51] A variety of opinions have been expressed on the detail of the most accurate way of quantifying emissions, and whether the data capture unforeseen events which can cause large emissions of methane (super-emitters).[52] This data, and the disputes surrounding it, are important for calculations of upstream emissions (particularly) from US LNG exports.

Generalisations from limited empirical data sets are completely understandable. given the lack of available data, but potentially problematic in relation to:

- Upstream data, which may be derived from a variety of relatively small production sites, compared with those based on much larger single fields;
- Upstream data from the US which are based on shale oil and gas operations are likely to be very different to those from conventional gas operations.[53]
- Older equipment – particularly pipelines and gas gathering infrastructure – which may have far higher emission rates than newer and more technologically advanced equipment.

Academic and NGO publications tend to conclude that methane emissions are substantially higher than reported by industry sources. This means that only transparent, independently verified and published emissions will achieve the required standard of credibility.

Satellite Data and `Super-Emitters'

Detailed analysis of methane emissions from both fossil and natural sources shows the dominance of a relatively small number of "super-emitters"[54], which account for a disproportionate amount of the total methane emissions released from all sources. Figure 4 (final column) identifies two types of super-emitters: accidents eg well blowouts, and network (pipeline or compressor) ruptures; and abandoned wells. A 2011 study of the US natural gas supply chain found that, on average, the top 10% of gas wells accounted for 70% of the fugitive methane emissions.[55] The Californian methane survey carried out over a two-year period found that 10% of point sources from all sectors contributed 60% of emissions. The largest source were landfills; emissions from

American shale oil and gas production "may have contributed more than half of all of the increased emissions from fossil fuels globally and approximately one third of the total increased emissions from all sources globally over the past decade." By contrast Nisbet et al. (2019) find that increases in emissions during 2014–2017 resulted mainly from non-fossil sources.

[49] Gaffney Cline (2020), Zhang et al. (2020).

[50] Elkind et al. (2020), Gaffney Cline (2020), Agerton et al. (2020).

[51] EPA (2020). See Gorchov Negron et al (2020) which cites results from aircraft measurements from offshore Gulf of Mexico platforms in 2018, which were a factor of two higher than those of EPA, principally due to higher platform counts and higher emissions from shallow water facilities.

[52] Lee, S. (2020).

[53] The vast majority of gas produced outside North America is from conventional gas operations.

[54] GIE and Marcogaz (2019), p.138. `The term 'super-emitter' can refer to malfunctioning equipment, particularly in unmanned installations where such equipment has the potential to exist for long periods of time. The determination of a super-emitter is best associated with emissions data from a given source and should not be viewed as an attribute of an entire site. Care should be taken when utilizing methodologies for identifying super-emitters to differentiate between episodic events (e.g. gas actuation events), erroneous measurements and/or malfunctioning equipment. The term 'fat-tail' is often used to describe the statistical representation of the data—a probability distribution that is highly skewed relative to a well-behaved distribution such as the normal or an exponential distribution. Having super-emitters at a few sites could skew significantly the distribution of emissions from a sample of sites.'

[55] Cited in Balcombe et al. (2015), Table 4, p.53. IEA (2017), p.412 cites a similar, more general percentage conclusion.

natural gas infrastructure were primarily associated with processing plants, compressor stations, refineries and power plants.[56]

Satellite monitoring is particularly effective in identifying super-emitters.[57] The Sentinel 5 and GHGSat satellites have been monitoring methane emissions at global and targeted levels, but during 2022-26 several more satellites will be launched with enhanced capabilities.[58] Data from the TROPOMI (tropospheric monitoring instrument) aboard Sentinel 5, launched by the EU-funded Copernicus programme are available from the French company Kayrros on a consultancy basis, which states that: ...`worldwide onshore sources of emissions are revisited with an average frequency of 3-4 days depending on weather conditions', and `Today's satellite imagery and artificial intelligence can detect and attribute well flaring and methane releases totalling more than 1GT of CO_2eq'.[59] Kayrros has carried out surveys of `visible methane' emissions – defined as greater than 5 tonnes per hour - over one and a half years. These emissions arise principally from bad practice or negligence and the biggest immediate value of satellite data will be to help operators to identify and eliminate these super-emitters, which Kayrros believes could be eliminated within 2-3 years.[60] While identification of super emitters is uncontroversial, accurate measurement of those observations is more problematic. Concentrations of emissions in methane and CO_2 columns use algorithms to arrive at measurements of methane.[61]

It is also important to understand that satellites are currently unable to identify emissions in regions which are offshore, snowy, marshy or have extreme humidity. In relation to suppliers of natural gas to Europe this means that: [62]

- satellites cannot view any methane emissions for Norwegian oil and gas production all of which is offshore[63];
- satellites cannot view Nigerian methane emissions due to humidity, as well as offshore production and marshy terrain);
- for Azerbaijan, methane emissions from offshore production for example from the Shah Deniz field would not be visible.
- In Russia: the Kayrros data confirms that pipeline emissions are significant but conform to Gazprom's reported emissions (see Section 3), most of the observations are maintenance events. Coverage of emissions from exploration and production activities is limited by snow cover. A large number of hotspots have been identified (although not quantified) near energy infrastructure in Siberia, the Urals and the Caucasus although whether from oil or gas operations, and whether connected to gas exports is not known.
- In Algeria, Kayrros has identified significant emissions of around 170,000 tonnes per year particularly from producing fields.
- In the US, the Permian Basin is a major emitter of 3mt/year, with above average methane intensity in spite of its large oil & gas production. However, when trying to identify emissions from specific LNG exports there are complex questions about how to identify the individual field from which the gas originates, and the specific pipeline route which it takes on the way to a specific LNG terminal.

---

[56] Duren et al. (2020).
[57] Nasralla, S. (2020).
[58] Elkind et al. (2020), Table 1.
[59] https://www.kayrros.com/methane-watch/ Accessed October 25, 2020. Kayrros (2020), p.3. Satellite imagery can be found in this source.
[60] Kayrros (2020). A 20% error on individual flow rates is possible and Kayrros converts methane volumes to CO_2 equivalent using a GWP of 84 x CO_2 (ie a 20 year time horizon see Figure 2).
[61] The algorithm for the TROPOMI Sentinel 5 measurement can be found in Hasenkamp et al. (2019).
[62] The national observations which follow are based on personal communication with Kayrros.
[63] Other OIES research has found that Norwegian emissions are extremely low. Hall (2020).

- Within Europe itself, no significant visible methane emissions were detected aside from in southern Poland which may be connected with coal production.

As technology advances, satellite capabilities along all of these parameters will undoubtedly improve. NASA's GeoCarb mission has been planned to provide, `wall-to-wall observations over the Americas..from the Southern tip of Hudson Bay to the southern tip of South America'.[64] How successful satellites will be in relation to much larger numbers of much smaller emissions (particularly from abandoned oil and gas wells and coal mines) is not yet clear. In late 2020, GHGSat launched a new satellite with much higher resolution which was able to confirm a controlled release of methane emissions at a rate of 260 kgCH_4/hr. GHGSat claims that its technology is able to detect methane emissions from sources 100 times smaller than any other satellite, with a resolution 100 times higher, and can detect and quantify methane emissions from point sources as small as oil and gas wells. The company will be launching 9 other high-resolution satellites by the end of 2022.[65] With the launch of more, and more sophisticated, satellites over the next few years monitoring and measurement capabilities will increase significantly.[66] However, it is important not to `oversell' these capabilities particularly in relation to small and diffuse sources, and emissions from surface conditions which prevent detection by the current generation of satellites.

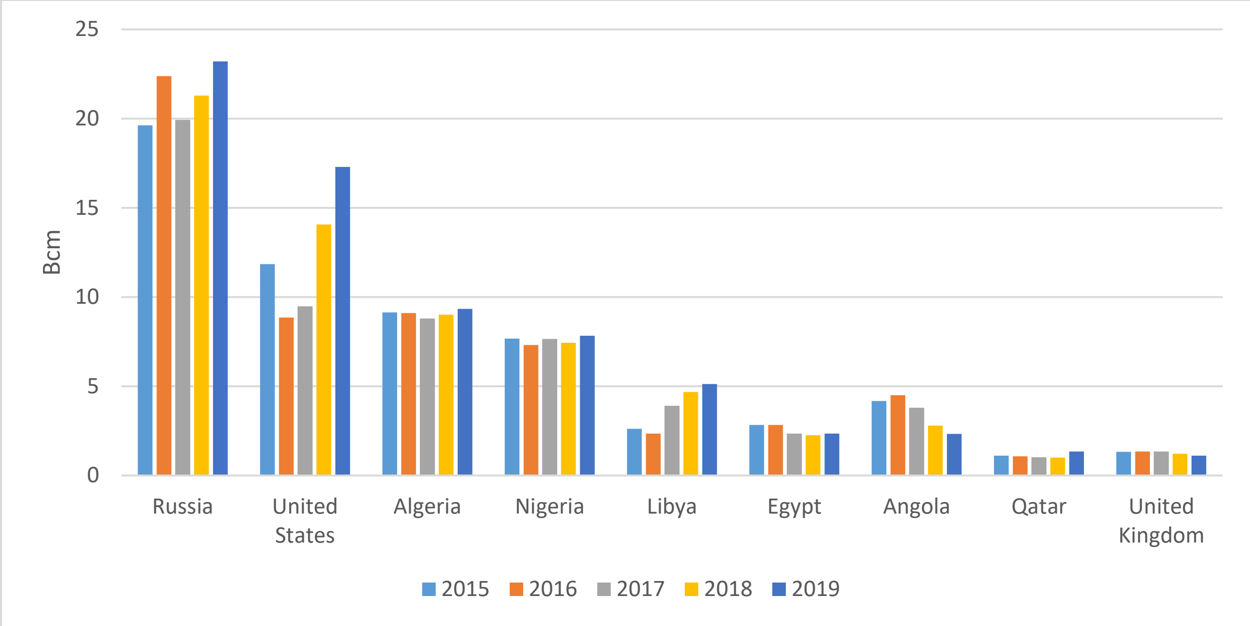
Gas Flaring

Flaring is one of the major categories of GHG emissions in the oil sector (Figure 5). The World Bank's Global Gas Flaring Reduction Partnership (GGFR) was established in 2002, and its aim is to eliminate routine flaring of gas by 2030 although flaring increased in many countries in 2019.[67] Figure 8 shows flared gas volumes over a five year period for countries which exported gas to Europe in 2019 (plus the UK for comparison).[68] Flared gas is largely combusted into carbon dioxide but – especially in substantial volumes – may contain fractions of unburnt methane.

GGFR publishes data for 30 countries to a level of just under 1 Bcm/year of flared gas and uses satellite data to detect flaring. The data are then calibrated using country level data.[69] GGFR is only focussed on flared natural or associated gas and does not separate emissions into carbon dioxide and methane, but it is unlikely that super-emitters identified by satellites (discussed above) include unburnt methane in flares. Nevertheless, although the data in Figure 8 show an increase in flaring, particularly in Russia and the US, this cannot be translated into any conclusions about methane emissions, and still less any conclusions about emissions from exports of natural gas and LNG to European countries.

[64] The most recent available account from Nasa (2018) states that `GeoCarb can scan the entire continental United States in about 2-1/4 hours, and from Brazil to South America's West Coast in about 2-3/4 hours.'
[65] GHGSat (2020).
[66] For example Environmental Defence Fund's MethaneSat expected to be launched in 2022.
[67] World Bank (2020).
[68] It does not show data for Azerbaijan – which are therefore assumed to be low – or for Norway which are known to be very low.
[69] The methodology used by GGFR can be found in Appendix 6.

Figure 8: Flared Gas Volumes 2015-19 (Bcm)



Source: World Bank (2020), p.5.

Measurement, Reporting and Verification Initiatives and Studies

Over the past decade, a number of different industry and government groups have set up voluntary initiatives to monitor and reduce fossil methane emissions especially from oil and gas. The major initiatives are: The Oil and Gas Methane Partnership Group (OGMP) of the UN Climate and Clean Air Coalition (CCAC), the Methane Guiding Principles, the Oil and Gas Climate Initiative (OGCI), the Collaboratory to Advance Methane Science (CAMS), the Global Methane Initiative, and ONE Future.[70]

Individual members of these groups have made corporate commitments to reduce emissions of methane (and CO_2) within defined time periods and have appointed their own certification organisations to report emissions.[71] While this is a significant step forward, these groups only focus on their own upstream emissions and not entire value chains. Exploration and production-related emissions are only one part of the value chain. National transmission and distribution networks must be included, as well as cross-border gas pipelines, LNG liquefaction, shipping and regasification terminals for countries with significant involvement in international trade.[72]

Within the European Union, industry bodies have collaborated to develop a value chain approach to methane emissions.[73] Gas Infrastructure Europe (GIE) and Marcogaz's Methane Emissions Action Plan cover the transportation and distribution segments of the natural gas value chain (including LNG) within the EU involving all the main industry associations, and the main requirements of data collection and reporting, as well as

---

[70] Oil and Gas Methane Partnership Group comprising 10 producing companies, the European Union, the Environmental Defense Fund and the United Nations Environment Programme. https://www.ccacoalition.org/en/activity/ccac-oil-gas-methane-partnership; Methane Guiding Principles https://www.ccacoalition.org/en/resources/reducing-methane-emissions-across-natural-gas-value-chain-guiding-principles ;Oil and Gas Climate Initiative (OGCI), http://oilandgasclimateinitiative.com/ comprising 13 producing companies; Collaboratory to Advance Methane Science (CAMS) https://methanecollaboratory.com/; Global Methane Initiative https://www.globalmethane.org in which 43 countries are involved comprising 70% of global anthropogenic emissions; ONE Future, http://onefuture.us/ comprising 22 companies from different parts of the gas value chain.

[71] For example OGCI is pledging to reduce the collective methane intensity of its member companies from a 2017 baseline of 0.32%, to below 0.25% by 2025, with the ambition to achieve 0.20%. OGCI (2020). IOGP and Marcogaz (2020) have set out guidelines for methane emissions target setting.

[72] For an analysis of decarbonisation requirements for LNG imports see Stern (2019).

[73] The bodies are principally: Gas Infrastructure Europe (GIE), Marcogaz and IOGP but also include the upstream voluntary associations such as OGCI, Methane Guiding Principles and others noted above.

harmonised methodologies and quantification of data.[74] From surveys of oil and natural gas value chains, the study estimates that methane emissions accounted for 1.3% of total GHG emissions in 2016, and that for the period 1990-2016 there was a 38% decrease in methane emissions mainly due to reductions from natural gas activities.[75] Table 1 shows detailed results from these surveys for each sub-segment. Methane emissions from gas transportation and distribution operations (utilisation excepted) were estimated at 0.6% of total EU GHG emissions in 2018 and no `super-emitters' (see above) were identified.[76]

Table 1: Methane Emissions from Transportation and Distribution Segments of EU Natural Gas Value Chains

	Percentage of European gas sales	Percentage of anthropogenic GHG emissions	Percentage of facility capacity included
TRANSMISSION	0.05%	0.08%	47%
DISTRIBUTION	0.1-0.2%	0.2-0.3%	43%
STORAGE	0.05% of total capacity/year	0.02%	34%
LNG REGASIFICATION TERMINALS	<0.002%	<0.003%	18 out of 20 terminals included

Sources: Marcogaz (2018a) p.4 and 23; Marcogaz (2018b) pp. 3-4; Marcogaz (2018c) pp. 4-5; Marcogaz (2018d) pp.4-5.

The GIE/Marcogaz study states that:

> 'Currently a number of gas companies use existing recognised standards and guidelines to assess and verify the methane emission inventories..However some additional work is needed in order to identify and quantify all different kinds of methane emissions and to report them along the entire value chain.'[77]

The EU Emissions Trading Scheme has established MRV procedures for CO_2 emissions which may serve as a (partial) template for methane and we return to this issue in Section 4.

Fuel switching methodologies and calculations

As part of the process of monitoring GHG reduction targets, it will also be important to verify the proposition that coal (and oil) to gas switching is a major and positive contribution to GHG emission reductions. Assessing the GHG advantages of coal to gas switching requires measurement of emissions of methane from coal mining and associated operations. We noted above that data on methane emissions from coal mining are lacking, fragmentary and complex (due to the different types of mines – see Section 2 and Appendix 5). Comparisons of emissions from coal and natural gas which compare carbon dioxide emissions from combustion of the two fuels, often add methane emissions from gas, but fail to include methane emissions from coal.[78]

Verification of methane emissions from both sources is essential to provide documentation as to whether fuel switching to natural gas does indeed yield GHG reduction benefits, and quantification of those benefits in relation to specific sources and value chains.[79] We should expect that there will be no uniform answer to the fuel switching question. Variances in emissions from individual gas, oil and coal sources and supply chains

[74] Marcogaz (2020).
[75] GIE and Marcogaz (2019), p.12. However, this estimate includes only emissions within the territory of the EU ie not including any emissions from imported natural gas or LNG; the exclusion of emissions from utilisation may be a potentially significant omission from the data.
[76] Ibid p.4.
[77] Ibid p.17. The most common ones are EHE Protocol, EN 15446 (VOCs but not all types of methane emissions), ISO 14064 (carbon footprint), high level ISO 14001 (environmental certification), ISO 50001 (energy efficiency) and ISAE 3000 (sustainability standards).
[78] The air quality advantages of gas over coal are an additional environmental consideration particularly in urban areas.
[79] It is worth noting that, aside from GHG reduction benefits, coal to gas switching has traditionally been and continues to be used in many countries to improve urban air quality.

mean that it will be important to document specific examples rather than generalisations. For example, where coal is being replaced by gas, there needs to be a comparison of the GHG (CO_2 plus methane) footprint of the coal which was being used, with the footprint of the gas which is replacing it. In the IEA's conclusions that:[80]

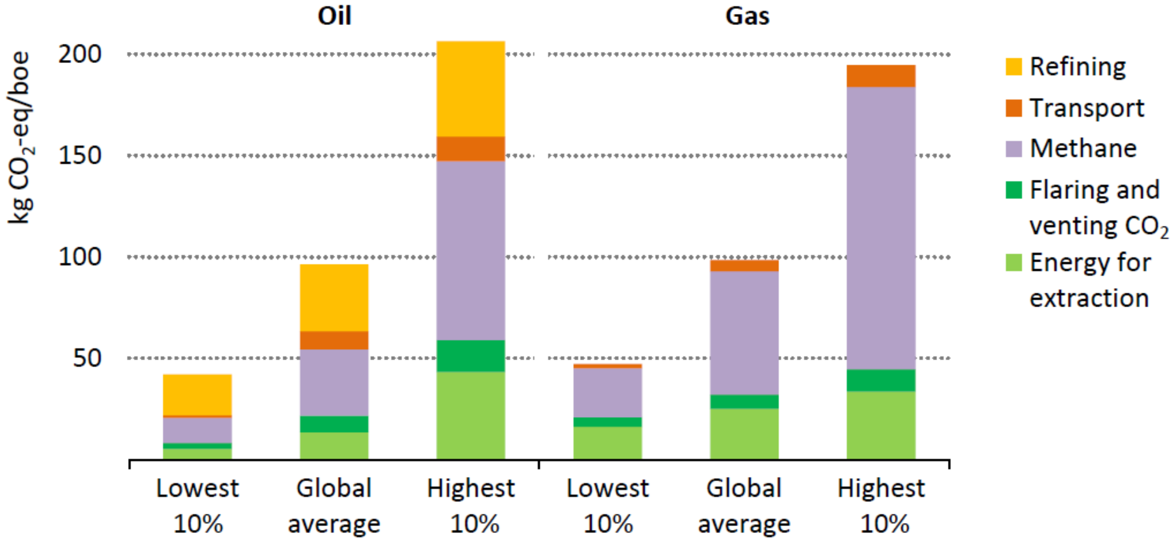
- on average, coal-to-gas switching reduces emissions by 50% when producing electricity and by 33% when providing heat;
- electricity produced from gas that has been transported as LNG results on average in 45% lower GHG emissions than coal;

The key phrase is `on average', but the Agency's data shows that the methane emissions intensity of coal from different countries varies significantly.[81] There will be an increasing requirement for much greater granularity of emissions from specific fossil fuel value chains to document the GHG advantages of fuel switching.

3. Calculating emissions from countries which export gas and LNG to the EU

Figure 9 illustrates a scale of GHG intensities from highest to lowest emitting sources of oil and gas. In both cases the highest 10% of the emitting sources is 3-4 times the lowest 10% and 2-3 times the average. However, in every case (with the exception of the lowest 10% of oil) methane is the largest component of emissions. An approximate rule of thumb from the gas data is that the lowest 10% have emissions of 50 kg CO_2-eq/boe, global average emissions are 100 kg CO_2-eq/boe and the highest 10% are twice the global average.

Figure 9: Lowest, Highest and Average Global GHG Emission Intensities of Oil and Gas Supply, 2017

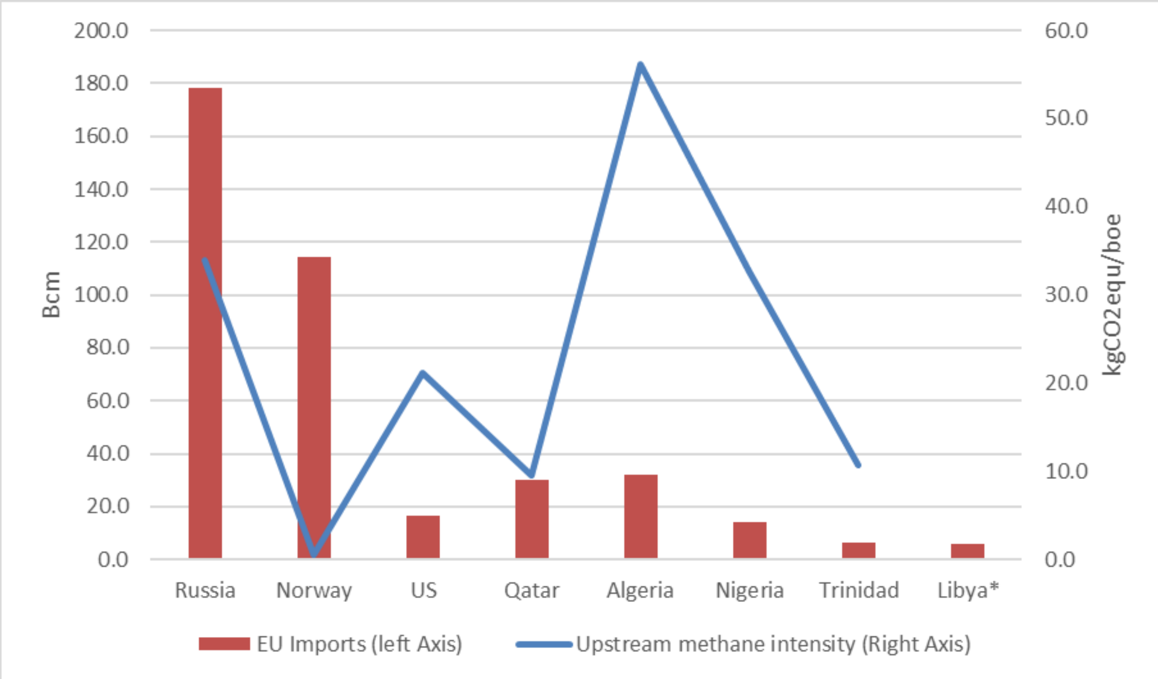


Source: IEA (2018), p.477.

In that context Figure 10 shows upstream methane intensity in 2019 of the countries which exported natural gas or LNG to the European Union compared with the volumes which they exported. It needs to be stressed that upstream methane intensity measures only the upstream (exploration and production) part of the value chain.

[80] IEA (2018), Box 11.3, p.490.
[81] IEA (2019a), Figure 5.16, p.249.

Figure 10: Methane intensity of exploration and production of oil and gas in countries which delivered more than 5 Bcm of natural gas and LNG to the European Union in 2019



*Libyan methane intensity was 277 kg CO_2 eq/boe.

Sources: Import data from IEA Natural Gas Information (online) 2020. Methane intensity data calculated by OIES derived from BP (2020) and IEA Methane Tracker Website.

To obtain the intensity of imported gas and LNG, emissions from pipeline transportation both inside the exporting country and between the latter and the EU would need to be measured, plus emissions from liquefaction and shipping in the case of LNG imports. Upstream intensity varies significantly between countries but for the major exporters to the EU it varies between Algeria at 56 kg CO_2-eq/boe and Norway at 0.5 kg CO_2-eq/boe with Russia (34), Nigeria (33) US (21) and Qatar (10) somewhere in between. For completeness we should note that LNG was also delivered to EU countries from Cameroon, Egypt, Peru, Equatorial Guinea and Angola, but deliveries from these countries in total amounted to around 3 Bcm (less than 0.01%) of EU imports in 2019.[82]

This data is increasingly important given the decline in domestic European (and EU) gas production signals rising import dependence. With the disappearance of Dutch exports, ongoing decline of UK production and relatively plateauing of Norwegian exports (neither of the latter two countries being EU members), increasing imports will be from countries which Figure 10 shows have higher methane intensity levels.[83]

Emissions from domestic EU production compared with imports

The European Commission's Methane Strategy (see Section 4) cites an estimate that the methane emissions associated with the gas and LNG imported into the EU were 'three to eight times the emissions occurring

[82] IEA Natural Gas Information (online) 2020. Note we refer here to deliveries to EU countries not to Europe as a whole which would include Turkey; deliveries from Azerbaijan to Turkey were around 10 Bcm of which probably less than half were transited to EU countries.

[83] For an assessment of UK and Norwegian gas production and export futures see Hall (2019) and Hall (2018), for their GHG upstream intensities see Hall (2020).

within the EU'.[84] This estimate for 2017 was calculated by Carbon Limits using two different methods and data sources:[85]

- Method 1 calculates emissions using IEA Methane Tracker estimates of national upstream emissions and the share of gas production exported from that country to the EU. `For example if 52% of the gas produced in Algeria was exported to the EU, then 52% of the country's upstream emissions were credited to exports of gas to the EU.' Transmission emissions from countries delivering gas by pipeline to the EU were also taken into account (although it is not clear how these were calculated).
- Method 2 estimated probabilistic emissions for conventional production using a model developed by Balcombe et al[86] and combined these with natural gas and LNG import data from the BP Energy Outlook (2017).

From these two methods, Carbon Limits derived a range of estimated methane emissions for imported natural gas and LNG of 232-615mt of CO_2eq compared with estimated methane emissions within EU borders (excluding distribution) of 76mt CO_2eq which results in imported natural gas emissions being 3-8 times higher than domestic emissions. Carbon Limits used a GWP for methane of 84 which assumes a time horizon of 20 years compared with the more usual GWP of 28 which assumes a 100 year horizon.[87]

IEA Methane Tracker data for 2019, disaggregated by sector for upstream and downstream oil and gas and attributable to flaring, venting and fugitive emissions in each sector, allows the methane emission intensity of upstream gas supply to be calculated for all major gas suppliers to the EU. Although UNFCCC provides data for transportation, the IEA does not separately identify midstream emissions, so we have taken upstream emissions as a proxy estimate of supply-side emissions to the EU. UNFCCC data show that for supply from most producing countries, most methane emissions arise in the upstream, not in the midstream. Since oil and gas are co-produced in most producer countries and emissions from oil and gas operations are often co-dependent, we have calculated national upstream emission intensity based on emissions from *all* upstream operations, not only those attributable by the IEA to `gas operations'.

The EU upstream sector produced about 95 bcm and emitted 387 kt of methane, equivalent to 10.8 mt CO_2e using a GWP of 28. This represents a methane emission intensity for EU gas production of 9 kgCO_2eq/boe.[88] Reproducing the calculation for upstream production in all countries which exported gas to the EU in 2019 (led by Russia, Norway, Algeria, Nigeria, Qatar and the US) yields a wide range of values for the methane emission intensity of upstream production shown in Figure 10. Weighting these values by the reported volume of gas delivered to the EU in 2019 from each country results in an average methane intensity of 28 kgCO_2e/boe.[89] This calculation confirms a ratio of about one to three between the methane emission intensity of EU production and EU gas imports; in other words, at the lower end of the range cited in the EU Methane Strategy from the Carbon Limits estimate although the latter include an allowance for transportation which ours does not. According to IEA data therefore, the upstream methane emission intensity of EU production is indeed much lower than the upstream methane emission intensity of countries which export gas to the EU.[90]

A high degree of caution is needed when using these data on comparisons of emissions. The IEA Methane Tracker data are themselves estimated emissions based on a variety of sources and assumptions (see Section 2 and Appendix 7) and can be very different, and often higher, than those reported by producer countries. They have fewer sectoral categories than the UNFCCC classifications and do not identify emissions

---

[84] This is from p.16 of European Commission (2020c) which erroneously attributes the estimate to the Environmental Defense Fund (EDF). Personal communication with EDF confirmed that the correct reference should be to Carbon Limits (2020).
[85] Carbon Limits (2020).
[86] Balcombe et al (2015) and (2018).
[87] See Section 1 Figure 2 for a discussion of GWP time horizons.
[88] Data in this paragraph has been calculated from the IEA Methane Tracker Website.
[89] Import data from IEA Natural Gas Information online data service (2020) with OIES adjustments for re-exports and allocating any unspecified source. There is a similar calculation in IEA (2019b), p.70 but this was made before the downward adjustment of Norwegian emissions.
[90] We can speculate this is due to more stringent environmental regulations and implementation of best practices, and that methane is a higher value product which in many EU countries has to be imported and therefore eliminating emissions can be achieved at net positive costs.

from domestic and international transportation, or from the LNG supply chain. Our estimate of emissions is based on upstream oil and gas, rather than the full supply chain to the EU border which risks under-estimating emissions from long pipeline transportation routes to the EU (eg from Russia) and from liquefaction and LNG shipping.

In some producer countries, the methane emission intensity of pipeline gas or LNG *export supply chains* may be quite different from that of *the upstream sector as a whole*. Long pipelines require more compressors which may have different efficiencies depending on their age; similar comments can be made about liquefaction plants and LNG ships.[91] For example where a single company or gas field (with little or no associated liquids production) accounts for all export volumes, and the domestic market is supplied separately, emissions may be very much lower than the national upstream average shown in Figure 10. The Nord Stream 1 pipeline, which supplies Russian gas to Europe, is sourced from dry gas fields on the Yamal Peninsula through a dedicated pipeline network to the offshore link to Germany. But Russian exports to Europe via other routes could contain co-mingled supply (from Russian and Central Asian sources) which could include associated gas and arrive via multiple transmission routes.

Similarly, the use of aggregated national upstream data may significantly mis-represent the emission intensity of LNG exports from the US Gulf Coast. In recent years, the gas produced in Texas, and in particular in the Permian Basin, has had a much higher methane emission intensity than gas produced across the rest of the Lower 48 states, because of high levels of flaring and venting.[92] But it is unclear from which specific fields US LNG exports are sourced and this may be difficult to determine if the liquefaction plants are being supplied by non-specific gas from transportation networks.

Russia and the US are very large countries with many gas fields and pipelines which substantially complicate tracing the physical supply chain from the wellhead to the point of export. However, even for a small country such as Qatar, where gas is largely produced from the North Field and transported through relatively short offshore pipelines to liquefaction plants, emission assessments are not entirely straightforward. More recent phases of the North Field have different liquid endowments to earlier phases and therefore emissions may differ.[93] In 2019, the Qatari government announced the construction of a carbon capture and storage plant which, combined with using CO_2 for enhanced oil recovery, would be sequestering 5mt of CO_2 by 2025.[94] It is assumed that the plant is designed to store the CO_2 from the new Qatari LNG trains which will be coming on stream around that time.

These complexities mean that simple calculations of methane emissions from gas deliveries to the EU, and devising national methane supply indices (as proposed in the EU Methane Strategy) are problematic. National methane intensities may be significantly different from intensities specific to pipeline and LNG export projects which will depend on physical value chain characteristics. Rather than applying *national* methane intensities, limiting MRV to intensities of *export supply chains* may be a less controversial, complex and costly, and more accurate, methodology for EU natural gas (and other fossil fuel) imports.

Case studies of methane intensity: Russia and the UK

Figure 11 demonstrates the problems of different measurement and reporting standards for national methane emissions using the case of Russia. There are orders of magnitude difference in these estimates and this is a result not just of different methods but also in the scope of emissions which are being reported. Data are for national emissions[95] except for Gazprom which is only for corporate emissions, but this is important because Gazprom is the sole exporter of Russian pipeline gas (but not LNG) to Europe. Gazprom data is published in the company's Environmental Report which for 2019 reported that emissions from production facilities

---

[91] For a comparison of GHG emissions from different liquefaction plants see Stern (2019), Figure 4, p.13.

[92] See Section 2 for further discussion of US emissions.

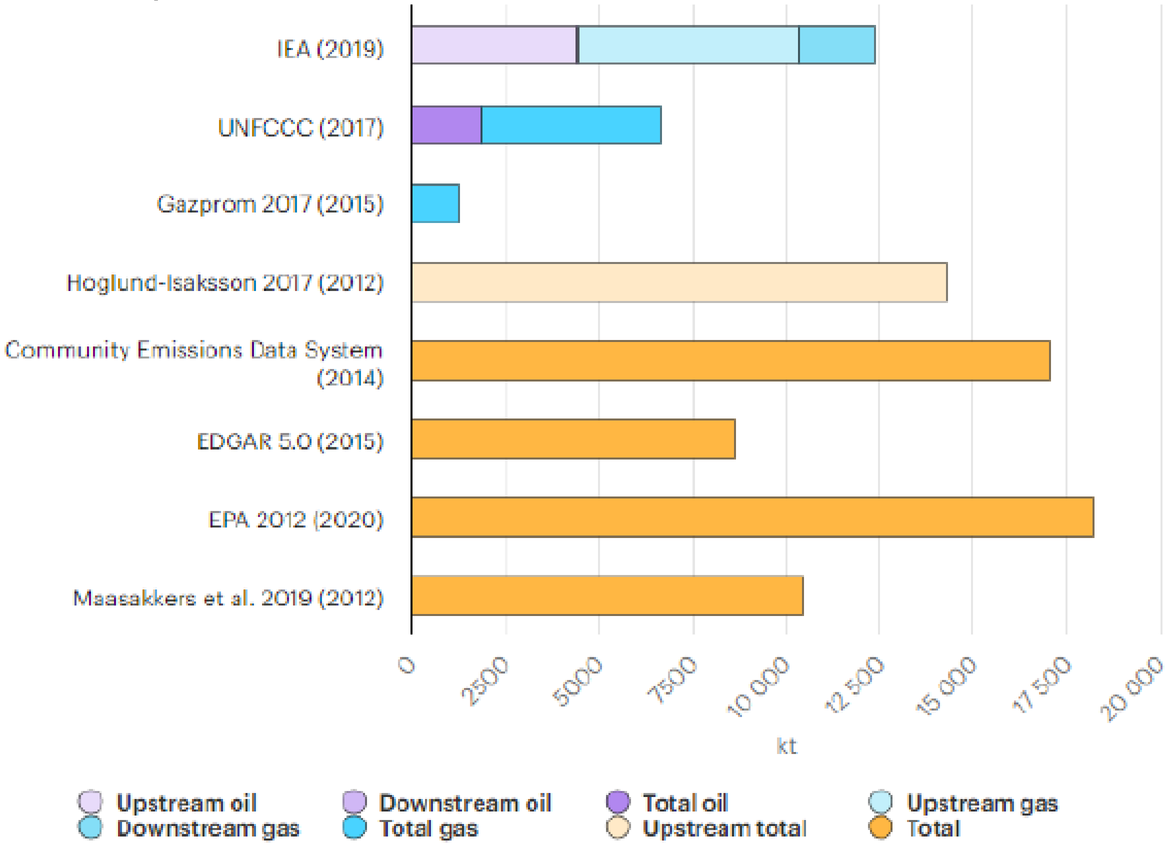
[93] Rogers (2019), pp.12-13.

[94] Paraskova (2019).

[95] The IEA's own national methane emissions estimates are 12.31mt of which 7.93mt is attributable to gas and 4.38mt to oil; 8.15mt venting, 3.75m fugitive and 0.41 incomplete combustion from flaring. https://www.iea.org/reports/methane-tracker-2020/interactive-country-and-regional-estimates#abstract

amounted to 0.02% of the volume of gas produced, 0.29% of the gas transported and 0.03% of gas stored.[96] The accounting firm KPMG provided a Limited Assurance Report that Gazprom's 2019 methane emission levels were 32.8mt CO_2 equivalent (1.2mt of methane at a GWP of 28).[97] The methane emissions of its biggest natural gas supplier are clearly a matter of considerable importance for the EU's, and individual member states', assessments of emissions from Russian gas imports will require a higher standard of verification than that provided by KPMG.[98] That said, Gazprom's emissions are transparently stated and certified in publicly available documents.

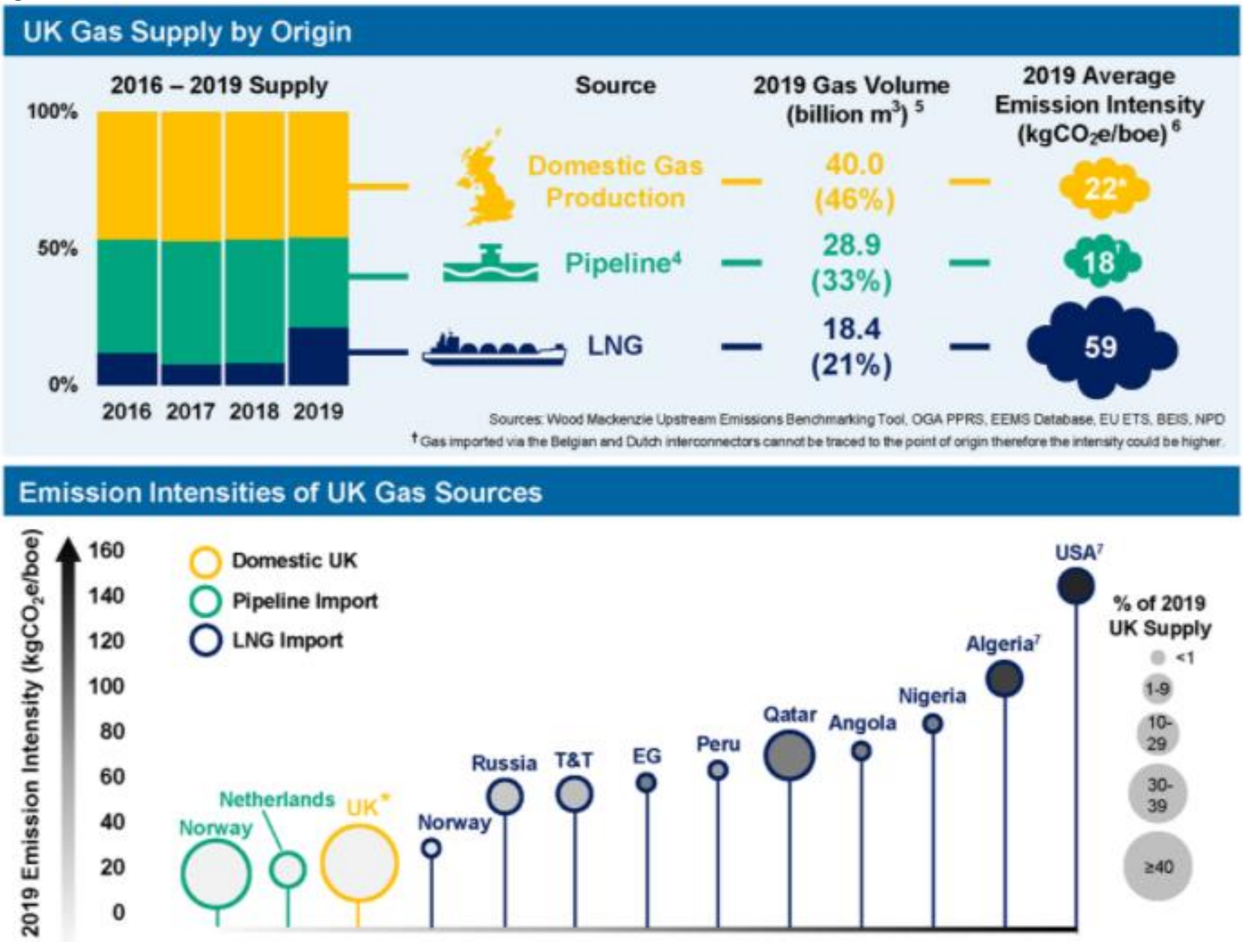
Figure 11: Comparison of Different Estimates of Russian Methane Emissions



Source: https://www.iea.org/reports/methane-tracker-2020/interactive-country-and-regional-estimates#abstract

[96] Gazprom (2019), p.57.
[97] Ibid, p.81.
[98] KPMG stated: "We conducted our limited assurance engagement in accordance with …3410 Assurance Engagements on Greenhouse Gas Statements issues by the International Auditing and Assurance Standards Board. That Standard requires that we plan and perform our procedures to obtain a meaningful level of assurance about whether the Management's Statement that the information on GHG emissions has been prepared…in accordance with the applicable criteria…and is free from material misstatement, is fairly stated."

Figure 12: GHG Emission Intensities of Sources of UK Gas 2016-19



Source: UK Oil and Gas Authority, *Benchmarking and Analysis*, https://www.ogauthority.co.uk/the-move-to-net-zero/net-zero-benchmarking-and-analysis/natural-gas-carbon-footprint-analysis/ Accessed 27 November 2020.

Comparative GHG emission intensities of individual sources of gas supplied to the UK (Figure 12) show that domestic UKCS production intensity is 22 kg CO_2-eq/boe, with Norwegian and Dutch pipeline imports slightly lower (but the latter cannot be traced to the point of origin).[99] Average LNG import intensity is 59 kg CO_2-eq/boe, slightly above the `lowest 10%' in Figure 9. Figure 12 also shows that intensity of different LNG sources varies considerably from around 30 kg CO_2-eq/boe for Norway, 50 for Russia and Trinidad, 70 for Qatar, 100 for Algeria, and more than 140 for US LNG which is high in relation to intensity rankings shown in Figure 9. However, it is important to notice that Figure 12 is based on benchmarking rather than actual measurements, and as such its accuracy can be questioned.

The Emergence of `Carbon-Neutral' LNG and a Contractual MRV Methodology for LNG Cargos in Asia

In 2019, the first LNG cargoes designated carbon-neutral were delivered to Japan, Korea and India by Shell and Jera. `Carbon neutral' in this context means that offsets have been purchased equivalent to the GHG emissions of the cargo. For the Shell deliveries of one cargo each to Tokyo Gas and GS Energy (in Korea) the GHG footprint of the entire LNG value chain was offset by purchasing emission credits from the company's own projects, including Katingan Peatland Restoration and Conservation Project in Indonesia and Cordillera

[99] Hall (2020), p.26 estimates UK upstream emission intensity at 28 kg CO_2e/boe and Norwegian intensity at 10 kg CO_2e/boe.

Azul National Park Project in Peru.[100] Jera purchased certified emissions reductions from Indian renewable electricity projects for a cargo sourced from Abu Dhabi equivalent to the emissions generated by the downstream use of the LNG in India; emissions associated with the production and transportation of LNG were not part of the carbon offset calculation.[101] In 2020, Shell delivered cargoes to CPC in Taiwan, with emissions offset by credits purchased from Shell's projects in Indonesia, Peru and Ghana.[102] The company also delivered 2 cargos to CNOOC in China with credits from Shell-supported afforestation projects from Qinghai and Xinjiang provinces.[103] Total delivered its first carbon neutral cargo to CNOOC from the Ichthys LNG plant in Australia. Emissions from the whole value chain footprint were offset using certificates from a wind power project in China and a forest protection project in Zimbabwe.[104]

There has been very little clarity in terms of methodology or costs of carbon neutral LNG. There is no way of knowing how the emissions footprint of the cargo, and the required volume of offsets, were calculated and whether these included only direct or also indirect emissions.[105] The additional cost for a carbon neutral cargo has been quoted as $2.4m which would add around $0.70-0.80/MMbtu to the cost, or more than 10% of Asian spot prices in late 2020.[106] At the time of writing, less than 10 carbon neutral cargos are known to have been sold and if this is to expand to encompass even a fraction of more than 5000 cargos sold every year, it seems likely that decarbonisation instruments other than offsets will need to be utilised.[107] In general, transparency of methodologies will be critical for the future credibility of carbon neutral LNG.

In 2020, Pavilion Energy issued a tender for up to 2mt of LNG over a five-year period, with supply to commence in 2023. The tender called for offers to collaborate on the development of a quantification and reporting methodology for the GHG content of deliveries and the company is understood to have received 25 offers of supply. A 10-year contract for up to 1.8mt/year of LNG starting in 2023 was signed with Qatar Petroleum Trading with additional contracts expected to follow.[108] This is a very different agreement to the individual carbon neutral cargoes discussed above. It is a long-term sale and purchase agreement, which does not require either seller or buyer to offset all of the emissions determined in accordance with the aforementioned methodology. The intention is to create a standardised methodology to quantify and report carbon and methane emissions from the supply chain of each individual cargo, from the wellhead through liquefaction and shipping to the delivery point (the entry point of the regasification terminal), which will be subject to verification by an accredited and independent expert. Pavilion Energy intends to make public these methodological principles with the possibility that they could become an industry standard. A further advantage of the methodology is that once emissions are measured, reported and verified in a standardised manner, Pavilion expects LNG industry players will be motivated to reduce their carbon and methane footprint through changes in their operations.

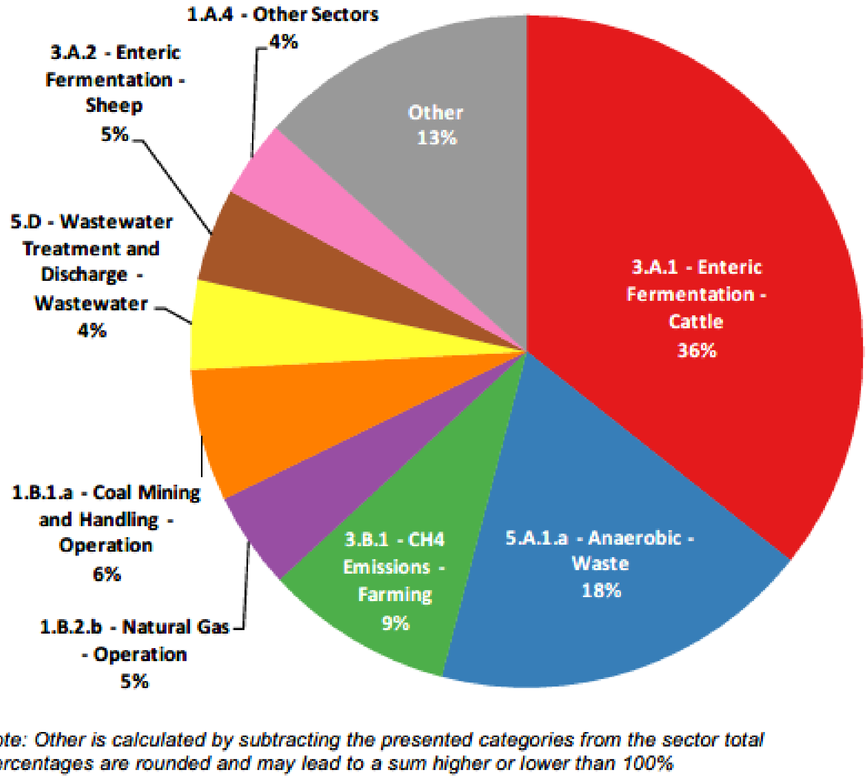
At the time of writing there were no similar LNG decarbonisation initiatives involving European importers. It would be expected that cargos claiming carbon neutrality would need to meet more stringent standards of methodology and data transparency set out in the EU Methane Strategy to which we now turn.

[100] Shell (2019).
[101] Jera (2019).
[102] Shell (2020a).
[103] Shell (2020b)
[104] Total (2020). The projects are the Hebei Guyuan Wind Power Project which aims to reduce emissions from coal-based generation in northern China and the Kariba REDD+Forest Protection Project which aims to protect Zimbabwe's forests.
[105] Shiryaevskaya and Krukowska (2020).
[106] Ibid, based on a standard cargo containing roughly 304,000 tonnes of CO_2.
[107] GIIGNL (2020) has substantial detail on LNG carbon offsetting. There is some scepticism about whether certain categories of offsets are truly `additional' or in other words whether `they would not have happened anyway'.
[108] Pavilion Energy (2020), Shiryaevskaya and Krukowska (2020).

4. The EU Methane Strategy

The EU Methane Strategy, published in October 2020, covers the energy, agriculture and waste sectors. It represents a significant policy advance because, although the Union's overall GHG emission targets are well known, `..there is currently no policy dedicated to the reduction of anthropogenic methane emissions'.[109]

Figure 13: Shares of Energy, Agriculture and Waste in Domestic EU Methane Emissions 2018



Source: European Environment Agency (2020), Figure 2.7, p.73.

The Strategy states that 53% of EU anthropogenic emissions come from agriculture, 26% from waste and 19% from energy; and that 54% of the methane emissions from the energy sector are from oil and gas, 34% from coal and 11% from residential and other final sectors.[110] These estimates do not seem consistent with the Union's GHG methane inventory data in Figure 13 which show gas and coal emissions at 11% with no mention of the oil sector (unless the `other' sector data contain a significant share of energy-related emissions).

Although energy-related methane emissions have halved since 1990 (compared with reductions of one third from waste and one fifth from agriculture), it is in the energy sector where the EU's climate target plan indicates that the most cost-effective methane emissions savings can be achieved.[111] The Strategy is very much focused on oil and gas, rather than coal, but there is recognition of emissions from both active and abandoned coal mines[112] (and also abandoned oil and gas wells), but the text gives the impression that there is a particular focus on imported natural gas and LNG. The Strategy is principally aimed at fossil sources of methane but also includes targeted support to accelerate the development of the market for biogas from sustainable

[109] European Commission (2020c), p.1.
[110] Ibid p.2-3. It is not clear whether the energy sector data are global or relate specifically to the EU. The Strategy cites the CCAC Scientific Advisory Panel as the (non-specific) source.
[111] Ibid pp.2-3. This is based on the work of the IEA (see Figures 6 and 7 above) and European Commission (2020b), Figure 70, p.87.
[112] European Commission (2018). The Commission will promote remedial work under the initiative for Coal Regions in Transition.

sources, principally non-recyclable human and agricultural waste and residues. But biogas derived from food or feed crops increases methane emissions and is therefore undesirable.[113]

The main aim of the Strategy is to create a more accurate measurement and reporting methodology which means Tier 3 reporting (see Appendix 2), which very few member states currently apply consistently, will be the EU target standard.[114] The Oil and Gas Methane Partnership (OGMP) 2.0 is the measurement and reporting framework adopted in the Strategy which proposes the creation of a Methane Observatory tasked with collecting, reconciling, verifying and publishing anthropogenic methane emissions data at a global level.[115]

The Observatory is proposed to be a collaboration between the United Nations Environmental Programme (UNEP) and the International Energy Agency (IEA) and would develop a Methane Supply Index against which emissions from individual countries would be judged.[116] The Commission is using its Copernicus Atmosphere Monitoring Service (CAMS) satellite capability to create an EU-coordinated capability for detecting and monitoring global super-emitters. Within the EU, the Strategy suggests that 10-20% of sites are responsible for 60-90% of emissions.[117] In 2025, CAMS will be enhanced with the launch of three new satellites which will allow more detailed monitoring, data sharing across stakeholders and more detailed analysis allowing for data reconciliation.

Legislative and regulatory requirements

In support of these aims, the Commission's new legislative proposals on the Green Deal (expected in mid-2021) will include:[118]

- Compulsory measurement, reporting, and verification (MRV) for all energy-related methane emissions, building on the Oil and Gas Methane Partnership (OGMP 2.0) methodology.
- Obligations to improve leak detection and repair (LDAR) of leaks from all fossil gas infrastructure, as well as any other infrastructure that produces, transports or uses fossil gas, including as a feedstock.
- Consideration of legislation on eliminating routine venting and flaring in the energy sector covering the full supply chain, up to the point of production. And also extension of the OGMP framework to more companies in the gas and oil upstream, midstream and downstream as well as to the coal sector and closed, as well as abandoned, sites.

The Strategy requires a review of EU climate and environmental legislation, notably the Industrial Emissions Directive and the European Pollutant Release and Transfer Register. The Zero Pollution Action Plan (2021), the third edition of the Clean Air Outlook (2022) and the National Emission Reduction Commitments Directive (2025) will also need to take its content into account.[119] There is little information on how the Strategy will impact energy regulation except that national regulatory authorities will be instructed to recognise the additional costs of leak detection and remediation and other MRV costs in the allowed revenues of networks.

The international dimension of the Strategy

Given the emphasis of this paper on emissions from EU imports of natural gas, the international dimension of the Strategy is particularly important. As discussed above[120], the Strategy cites an estimate that external

---

[113] European Commission (2020c), pp.7-8.
[114] Ibid. p.4.
[115] OGMP (2020). The Strategy (p.9.) describes OGMP 2.0 as `the best existing vehicle for improving measurement, reporting and verification capability in the energy sector'.
[116] Ibid. p.5. The Commission is ready to mobilise funding from the Horizon 2020 programme to kickstart the establishment of the Observatory and is envisaging a donor conference to encourage national governments to contribute towards its financing.
[117] Ibid. Note 37, p.6. attributed to: 'Tackling energy-related methane emissions', 2020. Consortium led by Wood Environment & Infrastructure Solutions GmbH. This study was not available at the time of writing.
[118] Ibid. p.11.
[119] Ibid. pp.6-7.
[120] See Section 3.

carbon or methane emissions associated with releases outside the EU, related to imported gas and LNG, are three to eight times the quantity of emissions occurring within the EU.

The Strategy proposes a coalition of importing countries – especially China, South Korea and Japan – to coordinate efforts on energy sector methane emissions. In 2019, those countries and the EU accounted for only 58% of global gas trade by pipeline, but 72% of global LNG trade.[121] The EU on its own accounts for more than half of global pipeline gas trade, and if it is successful in creating a coalition of major LNG buyers to support an ambitious international monitoring, reporting and verification standard this would have a significant impact on LNG trade.

The impact of the Strategy on exporting countries is potentially more important:[122]

> `The EU will lead a diplomatic outreach campaign to fossil fuel producer countries and companies and encourage them to become more active in the Oil and Gas Methane Partnership (OGMP)…[it will] explore the possibility of providing partner countries with technical assistance in gas and oil production so these countries can improve their methane regulatory frameworks and their capacity in monitoring, reporting and verification.'

But if the Commission does not believe that exporting countries are cooperating with this initiative, the Strategy is clear about the consequences:

> `In order to incentivise accurate measurement, reporting and verification (MRV) on fossil gas (including imports), the Commission will propose to use a default value for volumes that do not have adequate MRV systems in place. The default value will be applied where necessary until a compulsory MRV framework for all energy-related methane emissions building on the OGMP 2.0 methodology is implemented…In the absence of significant commitments from international partners, the Commission will consider proposing legislation on targets, standards or other incentives for fossil energy consumed and imported in the EU.'

Issues for natural gas exporters

The Strategy raises complex issues related to the time and cost required for implementation of its more radical proposals. Establishing the Methane Observatory – a new global body which will independently collate, reconcile and publish national and global data – could take several years. It could take time to agree the MRV procedures for creating the Methane Supply Index, with possible resistance from gas exporting governments and accusations of interference in their domestic affairs. However, almost all of the major gas exporters to Europe are members of the Global Methane Initiative which has strategic alliances with the United Nations Economic Commission for Europe (UNECE) and the Climate and Clean Air Coalition (CCAC).[123] The benefit of the UN umbrella is that it will be more difficult for a national government or company to resist requests from such a body, or to make accusations of discrimination. But it is likely that, to achieve compliance with the required MRV measures, some exporting governments will request not only technical but also financial support from either EU or UN institutions.

The Strategy contains a very clear threat to exporting countries to implement required MRV measures or risk having their exports to the EU deemed in excess of a future default emissions value to be established by the European Commission. This is a clear attempt to impose extra-territorial regulation on non-EU countries. The Strategy frames this as a 2-stage process: countries will be required to implement an approved MRV framework which allows their emissions to be determined. Having implemented the framework, they may be required to reduce their emissions below future thresholds to be established.[124] Failure to implement the framework will mean their emissions will be determined by a default value. Gas imports with methane emissions in excess of a default value, or in excess of defined thresholds would then be subject to financial

[121] BP (2020), pp. 42-3. Data include the UK which has since left the EU.
[122] Ibid, pp.16-17.
[123] https://www.globalmethane.org/about/index.aspx
[124] An *eventual* target threshold could be determined by the OGCI target to reduce upstream methane intensity to 0.2% by 2025. https://oilandgasclimateinitiative.com/ogci-reports-significant-progress-on-aggregate-upstream-methane-and-carbon-intensity-targets/

penalties determined by a future methane tax, carbon border adjustment mechanism or other GHG-related tax or price.[125]

The MRV which the EU will require from, or impose on, natural gas exporters is not yet clear. It could be based on the MRV framework which the EU has implemented in relation to CO_2 emissions under its Emission Trading Scheme. This includes monitoring plans and reports from operators which are required to be verified by reports from `accredited verifiers' and reviewed by `independent assessors'.[126] The EU regime may need to be significantly stricter than OGMP 2.0 which requires companies to use `reasonable and demonstrable efforts' to report emissions.[127] The Methane Strategy will require more stringent reporting and disclosure than OGMP2.0 which will risk conflicting with the (almost obsessive) confidentiality requirements, which often form part of international gas contracts.[128] Gas exporters and importers will need to understand that, aside from any legal/regulatory requirements, lack of transparency of MRV runs the risk that any claims which they make for emissions reduction will be dismissed as `greenwash'.

The Strategy's phrase `a diplomatic outreach campaign' suggests that the EU will try to achieve its aims by engagement, persuasion and inducements, rather than by compulsion and financial penalties. Diplomatic dialogue between individual member states and countries from which they import substantial volumes of gas will also be important. There are a number of legal obstacles of which the most important may be how financial penalties could be introduced without infringing WTO rules on discrimination. It will be significantly faster for the international dimension of the Strategy to be introduced by consensus rather than compulsion. The initial and principal focus needs to be on the major suppliers of gas to the EU – Norway, US, Qatar, Russia, Algeria and Nigeria. Given that Norway already has strong MRV in place and extremely low emissions, only five governments need to be persuaded to accept the EU MRV framework and future threshold values.[129]

As the Strategy recognises, it is companies (rather than governments) which export (and import) gas and will be required to deal with the logistical and commercial impacts of the Strategy. Table 2 shows the companies which accounted for 95% of the gas and LNG delivered to Europe in 2019, mostly under medium and long term, but also under portfolio, contracts.[130] For the majority of countries, gas is delivered by one or two companies which (in the cases of Algeria, Qatar, Nigeria, Azerbaijan, Libya and Russia's Novatek) also have joint venture partners, usually IOCs. Most of these companies are either state-owned or state controlled which again raises the prospect that government-to-government diplomacy may be important. At an export government level, this could be achieved through the Gas Exporting Countries Forum (GECF) whose members and observers include all the countries listed in Table 2 and almost all other countries which exported gas and LNG to EU countries in 2019, with the exception of the United States.[131]

---

[125] It is unlikely that methane imports would be included, at least initially, in any future Carbon Border Adjustment Mechanism which would more likely focus on energy intensive industrial sectors.
[126] For details see Commission Implementing Regulation (2018a) and (2018b).
[127] OGMP (2020), pp. 8-9.
[128] Ibid pp. 16-18 on external reporting and analysis and confidentiality.
[129] Trinidad and Tobago, Libya, Egypt and Angola could be added to this list but are currently marginal suppliers. Potential future suppliers in the Middle East, Central Asia and East Mediterranean regions could become relevant if proposed pipeline and LNG projects are completed.
[130] Calculated from BP (2020), pp. 42-43.
[131] https://www.gecf.org/countries/country-list.aspx Russia, Qatar, Algeria, Nigeria, Egypt and Equatorial Guinea are full members; Angola, Azerbaijan, Peru and Norway are observers

Table 2: Major Exporting Countries and Companies delivering Pipeline Gas and LNG to Europe in 2019

COUNTRY	COMPANIES WHICH DELIVERED SIGNIFICANT VOLUMES OF PIPELINE GAS AND LNG TO EUROPEAN CUSTOMERS IN 2019
	MEDIUM AND LONG TERM CONTRACTS
Russia	Gazprom, Novatek
Norway	Equinor
Algeria	Sonatrach
Qatar	Qatargas
Nigeria	Nigeria LNG
United** States	Cameron LNG, Total, Cheniere
Azerbaijan	Socar
Trinidad	Atlantic LNG
Libya	Libyan National Oil Company*
	PORTFOLIO** LNG SELLERS
	Shell, Total, Centrica, ENI, Equinor, Iberdrola, Naturgy

*The current political and military situation makes it difficult to know who is in charge of Libyan gas exports. **Although these companies sold LNG cargos to European buyers it is not certain that the cargos were delivered to European destinations. Likewise it is possible that cargos sold to Asian buyers could have been delivered to Europe.

Source: GIIGNL (2020), pp.10-17.

The US has a larger number of companies, both operators and offtakers, involved in exports of LNG to Europe which will increase as new projects are commissioned during 2020 and 2021. But despite the dominance of private companies, diplomacy may also be important in resolving problems. Therefore (with the possible exception of the US) the number of companies with which the EU may be required to negotiate on the details of the Strategy is relatively limited. There will be a larger number of buyers on the importing side, but these will be subject to the EU acquis. Understanding that negotiations are likely to be difficult, the Strategy should alert all stakeholders – EU and non-EU – that much tougher methane standards can be expected within a few years, and these must be taken into account particularly in respect of signing any new contracts for additional imports.[132]

[132] This may account for press reports that the French company Engie had withdrawn from negotiations on a long term contract for US LNG, following pressure from the French government and environmental organisations. Elliott and Weber (2020).

5. Summary and Conclusions

The subject of methane emissions is extremely challenging. The data are complex, difficult to understand (requiring substantial interpretation), disputed (or at least strongly debated) and often entirely lacking. Researchers have to work with data from different sources and collected using different methods and understand its limitations. Because domestic EU production of natural gas has been declining rapidly, there is an increasing EU focus on emissions from imported pipeline gas and LNG based not on standard factors but actual measurements. The EU Methane Strategy promises to be a significant milestone in that process. Companies which are supplying (or intending to supply) natural gas to the EU – the largest global market for pipeline gas and a very significant market for LNG - would be well advised to pay close attention to how the regulation of methane emissions is unfolding. Those outside the EU should note the start of similar corporate initiatives in Asian LNG trade.

Because methane is a much more powerful GHG than CO_2, accurate measurement has become an increasingly important issue. Despite the fact that methane emissions from agriculture (and in some countries waste) are significantly greater than those from fossil fuel production and use, it is the latter which are easiest and lowest cost, and therefore most urgent to substantially reduce. In an EU context, increasingly stringent GHG target reductions by 2030, have emphasised the urgency to focus on emissions from all fossil fuels. Emissions from oil and gas are difficult to disentangle because of co-production of associated gas. Coal, which accounts for more than one third of fossil methane emissions, is little discussed and data are even more problematic. In this context, to achieve credibility, emission reductions through coal (or oil) to gas switching will need verification of GHG emissions from specific value chains (not generalised combustion factors).

The main sources of oil- and gas-related methane emissions are from: incomplete combustion of flared gas and venting of methane from upstream operations; fugitive emissions from pipelines, storages and LNG facilities; post-meter emissions from end-user premises, and `super-emitters including emissions from accidents and abandoned wells. Most estimates of emissions are derived from ground level calculations based on standard emission values for specific processes or activities, multiplied by gas throughput volumes. Almost all these values are derived from US Environmental Protection Agency standards and are subject to uncertainty factors of plus or minus 10-30% (and sometimes much greater). Data derived from aeroplane and satellite measurements, are particularly useful for identifying `super-emitters' because 10-20% of the highest emitting sites can be responsible for 60-90% of a country's emissions.

The natural gas community is coming under increasing pressure to reduce methane emissions from its operations and this is most urgent in EU countries following the publication of the European Commission's Methane Strategy. `Community' means all stakeholders in natural gas value chains, including the major gas and LNG exporting companies. The Strategy has begun a process of creating a legal/regulatory framework in respect of transparent measurement, reporting and verification (MRV) of emissions based on the Oil and Gas Methane Partnership's voluntary commitments. This will require leak detection and repair of oil and gas infrastructure, as well as elimination of routine venting and flaring in energy supply chains. The Strategy proposes the creation of a methane emissions observatory under the auspices of the United Nations Environment Programme to collect, reconcile verify and publish data at a global level. Legislation will be published in mid-2021 with the intention that it will enter into force in early 2024. The anticipated outcome is a methane supply index from which will be established a methane emissions standard for imported gas and LNG which may be relatively relaxed (and therefore achievable) at the start of the regime, but will become progressively tougher over time. The EU will launch diplomatic initiatives to encourage other (particularly major Asian LNG) importing countries and major exporting countries, to adopt the proposed MRV framework.

The eventual aim will be the establishment of methane emission standards for all fossil fuels, but likely to apply particularly to natural gas, sold within the EU. Should countries which deliver gas to the EU fail to adopt this framework, then a default value will be established on which their emissions will be based, and it is assumed this will be used in respect of any future GHG (carbon or methane) prices or taxes which may be introduced. Enforcing the MRV framework on non-EU suppliers raises complex and potentially controversial legal issues in relation to WTO rules. However, these measures will significantly impact only a relatively small number of countries. Excluding Norway (where reported emissions data already meet any standard which may be imposed) the five countries where deliveries would be substantially and immediately impacted are: Russia, Qatar, USA, Nigeria and Algeria.

Of these, Russian pipeline gas may be the most important because of the size of deliveries and the fact that, unlike LNG exporters, it cannot reorient pipeline supplies to other markets. But countries can be expected to push back against the Strategy's proposal of a national methane supply index – which would assess emissions based on their entire oil and gas industries - against which their exports to the EU would be calibrated. Exporters are more likely to agree to the establishment of a methane emissions standard for pipeline and LNG export supply chains, measured and verified from the point of production to the border of the EU.

By 2024, when the Strategy is anticipated to be transposed into EU legislation, a combination of exporters and importers may be held jointly responsible to obtain methane verification reports from accredited institutions for the export supply chain of deliveries to European borders. The financial costs of compliance (or non-compliance) will require a negotiation in which governments which own or control exporting companies will need be involved, emphasising the need for diplomacy at EU and member state levels. There is the possibility that the Gas Exporting Countries Forum could negotiate with the European Commission on the detail of an MRV regime on behalf of exporters (with the exception of the US).

Much remains to be decided in respect of the future EU regime for methane emissions from natural gas. The initial focus on natural gas and LNG requires exporters and importers – as well as downstream stakeholders – to make an immediate and positive response to the Strategy. Failure to do so could accelerate the demise of natural gas in European energy balances faster than would otherwise have been the case, and provide less time to make the transition to decarbonised gases – specifically hydrogen – using existing natural gas infrastructure.

Finally, it is likely that this EU initiative will (and arguably already has) attracted attention from other governments and companies involved in global gas and LNG trade. Natural gas and LNG, if based on MRV requirements similar to those in the EU Methane Strategy, may be able to command premium prices from buyers eager to demonstrate their own GHG reduction credentials to governments, customers and civil society. Where the EU is leading other countries seem certain to follow, and this will result in methane emissions becoming an issue of substantial importance in global gas and LNG trade.

BIBLIOGRAPHY

Abrahams, L. S., Samaras, C., Griffin, M.W. and Matthews, H.S. (2015). "Lifecycle Greenhouse Gas Emissions from US Liquefied Natural Gas Exports: Implications for End Users." *Environmental Science and Technology*, 49: 3237–45.

Agerton, M., Gilbert, B. and Upton, G.B. (2020). *The Economics of Natural Gas Flaring in US Shale: an agenda for research and policy*, Baker Institute Working Paper, https://www.bakerinstitute.org/media/files/files/03160f6a/ces-agerton-etal-naturalgas-072420.pdf

Allen, M. (2017): *Climate metrics under ambitious mitigation*, Oxford Martin School Briefing, November 2017.

Alvarez, R. A. (and nine additional authors) (2018). "Assessment of Methane Emissions from the US Oil and Gas Supply Chain." *Science* 361: 186–8.

Balcombe, P., Anderson, K., Spiers, J., Brandon, N. and Hawkes, A. (2015). *Methane and CO_2 Emissions from the Natural Gas Supply Chain: An Evidence Assessment*. White Paper 1, Sustainable Gas Institute.

Balcombe, P., Anderson, K., Spiers, J., Brandon, N. and Hawkes, A. (2017). `The Natural Gas Supply Chain: The Importance of Methane and Carbon Dioxide Emissions.' *ACS Sustainable Chemistry and Engineering*, 2010, 5(1): 3–20.

Balcombe, P., Brandon, N.P. and Hawkes, A.D. (2018). `Characterising the distribution of methane and carbon dioxide emissions from the natural gas supply chain', *Journal of Cleaner Production* 172 (2018), pp. 2019-2032.

BP (2020): *BP Statistical Review of World Energy 2020*. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

Carbon Limits (2020): *Value chain methane emissions from natural gas imports in Europe*. https://www.carbonlimits.no/wp-content/uploads/2020/10/Methane_Value-Chain_Carbon-Limits.pdf

Commission Implementing Regulation (2018a): Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018. *On the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and to the Council and amending Commissions Regulation (EU) No 601/2012*.

Commission Implementing Regulation (2018b): Commission Implementing Regulation (EU) 2018/2067 of 19 December 2018. *On the verification of data and on the accreditation of verifiers pursuant to Directive 2003/87/EC of the European Parliament and to the Council*.

Dlugokencky, E. (2020), *Trends in Atmospheric Methane*, National Oceanic and Atmospheric Association, Earth System Research Laboratory, NOAA/ESRL. www.esrl.noaa.gov/gmd/ccgg/trends_ch4/ Accessed November 18, 2020.

Duren, R., Thorpe, A and McCubbin, I. (2020). *The California Methane Survey*, California Energy Commission, Publication Number: CEC-500-2020-047.

Elkind, J., Blanton, E., Denier Van Der Gon, H., Kleinberg, R.L. and Leemhuis, A. (2020): *Nowhere to Hide: the implications of satellite-based methane detection for policy, industry and finance*, Columbia: Center on Global Energy Policy.

Elliott, S. and Weber, H. `France's Engie pulls out of talks for US LNG import talks with NextDecade: Company'. S&P Global, *European Gas Daily*, November 4, p.3.

EPA (2020): *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2018*. US Environmental Protection Agency, EPA 430-R-20-002.

European Commission (2018): *Structural Support Action for Coal and Carbon-Intensive Regions*, https://ec.europa.eu/clima/sites/clima/files/docs/pages/initiative_5_support_en_1.pdf

European Commission (2020a): *Proposal for a Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law)*. COM(2020) 80 final.

European Commission (2020b): *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Stepping up Europe's 2030 Climate Ambition*, COM(2020) 562 final. Brussels, 17.9.2020

European Commission (2020c): *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions*, COM(2020) 663 final. Brussels, 14.10.2020

European Environment Agency (2020), *Annual European Union greenhouse gas inventory 1990-2018 and inventory report 2020*, Submission to the UNFCCC Secretariat, 27 May 2020. https://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2020

European Investment Bank (2019), Press Release, *EU Bank launches ambitious new climate strategy and Energy Lending Policy*, 14 November 2019. https://www.eib.org/en/press/all/2019-313-eu-bank-launches-ambitious-new-climate-strategy-and-energy-lending-policy

European Parliament (2020): Press Release, *EU climate law: MEPs want to increase 2030 emissions reduction target to 60%*. 08-10-2020.

https://www.europarl.europa.eu/news/en/press-room/20201002IPR88431/eu-climate-law-meps-want-to-increase-2030-emissions-reduction-target-to-60

Gaffney Cline (2020): *Tackling Flaring: learnings from leading Permian operators*, June 2020. https://www.gaffneycline.com/sites/g/files/cozyhq681/files/2020-06/Tackling%20Flaring_Final.pdf

Gazprom (2019): *Gazprom Environmental Report 2019*, https://www.gazprom.com/f/posts/72/802627/gazprom-environmental-report-2019-en.pdf

GGFR (2020): Global Gas Flaring Reduction Partnership, *Global Gas Flaring Tracker Report*, July 2020. http://pubdocs.worldbank.org/en/503141595343850009/WB-GGFR-Report-July2020.pdf

GHGSat (2020): *Smallest Methane Emission Ever Detected by Satell*ite, October 8, 2020. https://www.ghgsat.com/smallest-methane-emission-ever-detected-by-satellite/

GIE and Marcogaz (2019): *Potential ways the gas industry can contribute to the reduction of methane emissions*, Report for the Madrid Forum (5-6 June 2019). https://www.gie.eu/index.php/gie-publications/methane-emissions/methane-emission-report-2019/27786-gie-marcogaz-report-for-the-madrid-forum-potential-way-gas-industry-can-contribute-to-the-reduction-of-methane-emissions/file

GIIGNL (2020): *LNG Carbon Offsetting: fleeting trend or sustainable practice?* LNG Insight, 16/06/20.

Gorchov Negron, A.M., Kort, E.A., Conley, S.A. and Smith, M.L. `Airborne Assessment of Methane Emissions from Offshore Platforms in the U.S. Gulf of Mexico', *Environmental Science and Technology*, 2020, 54, 5112-5120.

Hall, M (2018): *Norwegian Gas Exports – Assessment of Resources and Supply to 2035*, OIES Paper NG127.

Hall, M. (2019): *Gas Production from the UK Continental Shelf: An Assessment of Resources, Economics and Regulatory Reform*, OIES Paper NG148.

Hall, M. (2020): *Net Zero Targets and GHG Emission Reduction in the UK and Norwegian Upstream Oil and Gas Industry: A Comparative Assessment*, OIES Paper NG 164.

Hasekamp, O., Lorente, A., Hu, H., Butz, A., aan de Brugh, J., and Landgraf, J. (2019), *Algorithm Theoretical Baseline Document for Sentinel-5 Precursor Methane Retrieval*, SRON Netherlands Institute for Space Research, Document No: SRON-S5P-LEV2-RP-001.

Howarth, R. W. (2019). 'Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane?', *Biogeosciences*, 16, 3033–3046, https://doi.org/10.5194/bg-16-3033-2019 .

ICF (2016a): *Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems*. Fairfax, VA, United States: ICF.

ICF (2016b): *Summary of Methane Emission Reduction Opportunities Across North American Oil and Natural Gas Industries*. Fairfax, VA, United States: ICF.

IEA (2017): *World Energy Outlook 2017*, Paris: IEA/OECD.

IEA (2018): *World Energy Outlook 2018*, Paris: IEA/OECD.

IEA (2019a): World Energy Outlook 2019, Paris: IEA/OECD

IEA (2019b): *The Role of Gas in Today's Energy Transitions*, Paris: IEA/OECD.

IEA (2020a): *World Energy Model Documentation*, Paris: IEA/OECD.

IEA (2020b): *Sustainable Recovery*, Paris: OECD/IEA.

IEA (2020c): *Global Methane Emissions from Oil and Gas: insights from the updated IEA Methane Tracker*, March 2020. https://www.iea.org/articles/global-methane-emissions-from-oil-and-gas

IEA Methane Tracker Website: https://www.iea.org/reports/methane-tracker-2020/interactive-country-and-regional-estimates#abstract All references accessed November 22, 2020.

IOGP and Marcogaz (2020) *Guidelines for Methane Emissions Target Setting*, https://www.marcogaz.org/publications-1/documents/

IPCC (2014): *Mitigation of Climate Change: Contribution of Working Group 3 to the Fifth Assessment Report of the International Panel on Climate Change*. Ed. O. Edenhofer et al, Cambridge: Cambridge University Press.

IPCC (2006): *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

IPCC (2019): *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol2.html

IPCC (2020): *Tiers of Emission Factors and Activity Data*, https://community.foundationfootprint.com/FoundationFootprintHelpCentre/Miscellaneous/IPCCTiers.aspx. (Accessed March 2020) The full IPCC emission factor database can be found at https://www.ipcc-nggip.iges.or.jp/EFDB/main.php

Jackson, R.B. (and 9 additional authors) (2020): `Increasing anthropogenic emissions arise equally from agricultural and fossil fuel sources'. *Environmental Research Letters* (15). https://iopscience.iop.org/article/10.1088/1748-9326/ab9ed2

JERA (2019): `JERA Global Markets Pte. Ltd. First Carbon-Neutral LNG Delivery into India', June 27, 2019, http://www.jeragm.com/press-releases/JERA-Global-Markets-Pte-Ltd-first-carbon-Neutr-(1)

Kayrros (2020): *Eliminating Methane Super Emitters*, Kayrros White Paper, November 2020.

Kirschke, S. (and 47 additional authors) (2013): `Three Decades of Global Methane Sources and Sinks', *Nature Geoscience*, Volume 6, October 2013, pp.813-823.

Lee, S. (2020). `EPA Estimate Undercounts Methane Emissions, Environmentalists Say', https://www.bloomberg.com/news/articles/2020-04-17/epa-estimate-undercounts-methane-emissions-environmentalists Accessed August 31, 2020.

Marcogaz (2018a): *Survey Methane Emissions for Gas Transmission in Europe*,

Marcogaz (2018b): *Survey Methane Emissions for Gas Distribution in Europe*,

Marcogaz (2018c): *Survey Methane Emissions for Gas Storage Facilities (UGS) in Europe*,

Marcogaz (2018d): *Survey Methane Emissions for Terminals in Europe*,

Marcogaz (2020): *Methane Emissions Action Plan*, https://www.marcogaz.org/publications-1/documents/

Nace, T., Plante, L. and Browning, J. (2019). `The New Gas Boom: Tracking Global LNG Infrastructure', *Global Energy Monitor*.

NASA 2018: Geo-Carb: a new view of carbon over the Americas, January 11, 2018. https://www.nasa.gov/feature/jpl/geocarb-a-new-view-of-carbon-over-the-americas

Nasralla, S. (2020): `Satellites reveal major new gas industry methane leaks', Reuters, June 26, 2020. https://www.reuters.com/article/us-climatechange-methane-satellites-insi/satellites-reveal-major-new-gas-industry-methane-leaks-idUSKBN23W3K4

National Academic of Sciences (2018): *Basin Methane Reconciliation Results*. https://energy.colostate.edu/media/sites/147/2018/10/BasinMethaneOverview.pdf

Nisbet, E. G. (and nine additional authors) (2019). "Very Strong Atmospheric Methane Growth in the 4 Years 2014–2017: Implications for the Paris Agreement." *Global Biogeochemical Cycles* 33 (3): 318–42. https://doi.org/10.1029/2018GB006009

OGCI (2020): *OGCI reports significant progress on aggregate upstream methane and carbon intensity targets*, October 19, 2020. https://oilandgasclimateinitiative.com/ogci-reports-significant-progress-on-aggregate-upstream-methane-and-carbon-intensity-targets/

OGMP (2020): *Mineral Methane Initiative OGMP2.0 Framework*, 19 November, 2020. https://www.eenews.net/assets/2020/11/23/document_ew_06.pdf

Paraskova, T. (2019): `Qatar Builds The Biggest Carbon Capture Plant In The Middle East', *Oil Price*, October 8, 2019. https://oilprice.com/Latest-Energy-News/World-News/Qatar-Builds-The-Biggest-Carbon-Capture-Plant-In-The-Middle-East.html

Pavilion Energy (2020): `Temasek-owned Pavilion Energy calls for offers to pave the way for carbon neutral LNG supply', 2 April 2020. https://www.pavilionenergy.com/news-20200402-01.html

Rogers, H. (2019): `Qatar: LNG expansion following the ending of the North Field Moratorium', in Stern, J.P. ed. *The Future of Gas in the Gulf: continuity and change*, OIES: 2019. Chapter 1.

Saunois, M. (and 90 additional authors) (2020): `The Global Methane Budget 2000-2017', *Earth System Science Data, 12*. https://essd.copernicus.org/articles/12/1561/2020/

Shell (2019): `Tokyo Gas and GS Energy to receive world's first carbon neutral LNG cargoes from Shell', June 18, 2019. https://www.shell.com/business-customers/trading-and-supply/trading/news-and-media-releases/tokyo-gas-and-gs-energy-to-receive-worlds-first-carbon-neutral-lng-cargoes-from-shell.html

Shell (2020a): CPC Corporation, `Taiwan receives carbon neutral LNG cargo from Shell', March 4, 2020 https://www.shell.com/business-customers/trading-and-supply/trading/news-and-media-releases/cpc-corporation-taiwan-receives-carbon-neutral-lng-cargo-from-shell.html

Shell (2020b): `CNOOC to receive Chinese mainland's first carbon neutral LNG cargoes from Shell', June 22, 2020. https://www.shell.com/business-customers/trading-and-supply/trading/news-and-media-releases/cnooc-to-receive-chinese-mainlands-first-carbon-neutral-lng-cargoes-from-shell.html

Shiryaevskaya, A. and Krukowska, E. (2020): Gas Shippers seek profit from delivering `carbon-neutral' LNG, *Bloomberg News*, 25 October 2020.

Stern (2019): *Challenges to the Future of LNG: decarbonisation, affordability and profitability*, OIES Paper NG152.

Total (2020): *Total delivers its first carbon neutral LNG cargo*, 20/10/20. https://www.total.com/media/news/communiques-presse/total-delivers-its-first-carbon-neutral-lng-cargo

Townsend-Small, A., Ferrara, T.W., Lyon, D.R., Fries, A.E. & Lamb, B.K. (2016). `Emissions of coalbed and natural gas methane from abandoned oil and gas wells in the United States', *Geophysical Research Letters 43*, 2283-2390.

UNFCCC (2015): https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

UNFCCC (2019): *Report on the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on the third part of its first session, held in Katowice from 2 to 15 December 2018*. FCCC/PA/CMA/2018/3/Add.2.

UNFCCC (2020): *United Nations Climate Change Report 2019*.

Wang, C-K., Luo, X-Z. and Zhang. H. (2013) `Shares of Differences of Greenhouse Gas Emissions Calculated with GTP and GWP for Major Countries', *Advances in Climate Change Research* 4(2): 127-132, 2013. DOI: 10.3724/SP.J.1248.2013.127

World Bank (2020): Global Gas Flaring Reduction Partnership, https://www.worldbank.org/en/programs/gasflaringreduction

Zhang, Y. et al. (17 additional authors) (2020): "Quantifying Methane Emissions from the Largest Oil-Producing Basin in the United States from Space." *Scientific Advances* 6 (17): eaaz5120.

APPENDIX 1. Sources of Methane Emissions from the Gas Value Chain

	CATEGORIES OF METHANE EMISSIONS		
MAIN SOURCES OF METHANE EMISSIONS FROM THE GAS CHAIN	FUGITIVES	VENTING	INCOMPLETE COMBUSTION
Production	Components (valves, flanges, connectors, etc.)	Flaring Tank storage; Compressors; Maintenance; Failure/Emergency; Glycol regeneration; Produced water handling; Pneumatic controllers	Flaring[13]; Stationary combustion devices (e.g. gas turbines, engines, boilers); Turbo compressors
Liquefaction	Components (valves, flanges, connectors, etc.) ; Compressor seals	Flaring Tank storage Vessels and truck loading Maintenance Failure/Emergency Start-up/shutdown activities	Flaring; Stationary combustion devices (e.g. engines, boilers)
LNG carriers	Components (valves, flanges, connectors, etc.)	Tanks; Compressors; Gas freeing for dry-dock; Start & stops	Engines (e.g. Methane slips)
Biomethane production	Open digestate storage; Separator; Storage of solid fraction; Biofilter; Valves	Flaring Closed digestate storage; Reactor Maintenance	Flaring; CHP
	CATEGORIES OF METHANE EMISSIONS		
	FUGITIVES	VENTING	INCOMPLETE COMBUSTION
Transmission & storage[14] (includes compressor stations, regulation and measurement stations, pipelines, underground storage)	Components (valves, flanges, connectors, etc.)	Compressors; Maintenance; Failure/Emergency; Pneumatic controllers; Devices for on-line gas quality sampling	Stationary combustion devices (e.g. engines, boilers) Engines/Turbines for gas compression Flaring
Regasification	Components (valves, flanges, connectors, etc.)	Flaring Vessels and truck loading; Vessels unloading; Maintenance; Failure/Emergency; Pneumatic controllers	Stationary combustion devices (e.g. engines, boilers); Vaporisers; Flaring
Distribution	Components (valves, flanges, connectors, etc.); Permeability of materials	Maintenance; Failure/Emergency; Operational	Stationary combustion devices (e.g. boilers)
Utilisation - Road transport	Devices; Connections	Start & stops	Unburnt
Utilisation - Maritime transport	Devices; Connections	Start & stops; Failure	Unburnt
Utilisation - Power generation	Devices; Connections	Start & stops; Maintenance; Failure	Unburnt
Utilisation - Chemical feedstock	Blending; Connections	-	Incomplete reaction
Utilisation - Industrial	Devices; Connections	Start & stops; Maintenance; Failure	Unburnt
Utilisation- Commercial	Devices; Connections	Start & stops	Unburnt
Utilisation - Residential	-	Start & stops	Unburnt

Source: GIE and Marcogaz (2019), Table 1, pp.13-14.

APPENDIX 2: IPCC Definitions of Tiers[133]

There are three Tiers presented in the 2006 IPCC Guidelines for estimating emissions from fossil fuel combustion. These are the reference for compilers of National Greenhouse Gas inventories.

TIER 1

The Tier 1 method is fuel-based, since emissions from all sources of combustion can be estimated on the basis of the quantities of fuel combusted (usually from national energy statistics) and average emission factors. Tier 1 emission factors are available for all relevant direct greenhouse gases.

The quality of these emission factors differs between gases. For CO_2, emission factors mainly depend upon the carbon content of the fuel. Combustion conditions (combustion efficiency, carbon retained in slag and ashes etc.) are relatively unimportant. Therefore, CO_2 emissions can be estimated fairly accurately based on the total amount of fuels combusted and the averaged carbon content of the fuels.

However, emission factors for methane and nitrous oxide depend on the combustion technology and operating conditions and vary significantly, both between individual combustion installations and over time. Due to this variability, use of averaged emission factors for these gases, that must account for a large variability in technological conditions, will introduce relatively large uncertainties.

TIER 2

In the Tier 2 method for energy, emissions from combustion are estimated from similar fuel statistics, as used in the Tier 1 method, but country-specific emission factors are used in place of the Tier 1 defaults. Since available country-specific emission factors might differ for different specific fuels, combustion technologies or even individual plants, activity data could be further disaggregated to properly reflect such disaggregated sources. If these country-specific emission factors indeed are derived from detailed data on carbon contents in different batches of fuels used or from more detailed information on the combustion technologies applied in the country, the uncertainties of the estimate should decrease, and the trends over time can be better estimated.

TIER 3

In the Tier 3 methods for energy, either detailed emission models or measurements and data at individual plant level are used where appropriate. Properly applied, these models and measurements should provide better estimates primarily for non-CO2 greenhouse gases, though at the cost of more detailed information and effort.

Continuous emissions monitoring (CEM) of flue gases is generally not justified for accurate measurement of CO_2emissions only (because of the comparatively high cost) but could be undertaken particularly when monitors are installed for measurement of other pollutants such as SO2 or NOx. Continuous emissions monitoring is particularly useful for combustion of solid fuels where it is more difficult to measure fuel flow rates, or when fuels are highly variable, or fuel analysis is otherwise expensive. Direct measurement of fuel flow, especially for gaseous or liquid fuels, using quality assured fuel flow meters may improve the accuracy of CO_2 emission calculations for sectors using these fuel flow meters. When considering using measurement data, it is good practice to assess the representativeness of the sample and suitability of measurement method. The best measurement methods are those that have been developed by official standards organisations and field-tested to determine their operational characteristics.

[133] IPCC (2006), Volume 2, Chapter 1. Section 1.3.1.1, pp.1.6-1.8. These paragraphs are copied from the source.

APPENDIX 3. Methane Emission and Uncertainty Factors for the Natural Gas Value Chain - Tier 1

Table A3.1: Natural Gas Exploration, Production and Processing*

SEGMENT		VALUE	UNCERTAINTY FACTOR %	UNITS OF MEASURE
EXPLORATION				
Onshore unconventional without flaring or gas capture		20.1	+/-20%	Tonnes/unconventional onshore gas wells drilled in a year without flaring or recovery
		4.35	+/-20%	Tonnes/total unconventional onshore gas well population where exploration occurs without flaring or recovery
		2.52	+/-20%	Tonnes/million cubic metres unconventional onshore gas production where exploration occurs without flaring or recovery
Onshore unconventional with flaring or gas capture		1.3	+/-20%	Tonnes/unconventional onshore gas wells drilled in a year with flaring or recovery
		0.05	+/-20%	Tonnes/total unconventional onshore gas well population where exploration occurs with flaring or recovery
		0.08	+/-20%	Tonnes/million cubic metres unconventional onshore gas production where exploration occurs with flaring or recovery
Onshore conventional exploration		5.78	+/-20%	Tonnes/conventional onshore gas wells drilled in a year
		0.03	+/-20%	Tonnes/total conventional onshore gas well population
		0.06	+/-20%	Tonnes/million cubic metres conventional onshore gas production
PRODUCTION				
Onshore: most activities occurring with higher-emitting technologies and practices		4.09	+/-20%	Tonnes/million cubic metres onshore gas production
		7.07	+/-20%	Tonnes/active gas well
Onshore: most activities occurring with lower-emitting technologies and practices		2.54	+/-20%	Tonnes/million cubic metres onshore gas production
		4.37	+/-20%	Tonnes/active gas well
Onshore Coal Bed Methane		1.95	+/-20%	Tonnes/million cubic metres onshore gas production
Gathering		3.20	+/-10%	Tonnes/million cubic metres onshore gas production
Offshore		2.94	+/-20%	Tonnes/million cubic metres offshore gas production

PROCESSING			
Without LDAR** or with limited LDAR, or less than 50% of centrifugal compressors have dry seals	1.83	+/-10%	Tonnes/million cubic metres of gas processed
	1.65	+/-10%	Tonnes/million cubic metres of gas processed
Extensive LDAR, and 50% or more of centrifugal compressors have dry seals	0.75	+/-10%	Tonnes/million cubic metres of gas processed
	0.57	+/-10%	Tonnes/million cubic metres of gas processed
Sour Gas (acid gas removal)	0.1	+/-100%	Tonnes/million cubic metres of gas processed

*Exploration values from US EPA; production values from US EPA, Australian National Greenhouse gas and energy reporting program, and US Bureau of Ocean Energy Management. Processing values from US EPA and 2006 Guidelines. **leak detection and repair

Source: IPCC (2019), Volume 2, Chapter 4. Tables 4.2.4F, 4.2.4G and 4.2.4H, pp.4.66-4.67, 4.70-4.71, 4.73.

Table A3.2: Natural Gas Transmission and Storage, LNG Import/Export and Storage, Distribution and Post-meter Segments - Tier 1*

SEGMENT		VALUE	UNCERTAINTY FACTOR %	UNITS OF MEASURE
TRANSMISSION				
Limited LDAR or less than 50% of centrifugal compressors have dry seals		3.36	-20% to +30%	Tonnes/million cubic metre of gas consumption
		4.10	-20% to +30%	Tonnes/kilometre of pipeline
Extensive LDAR or more than 50% of centrifugal compressors have dry seals		1.29	-20% to +30%	Tonnes/million cubic metre of gas consumption
		2.08	-20% to +30%	Tonnes/kilometre of pipeline
STORAGE				
Limited LDAR and most activities occurring with higher-emitting technologies and practices		0.67	-20% to +30%	Tonnes/million cubic metre of gas consumption
Extensive LDAR and lower-emitting technologies and practices		0.29	-20% to +30%	Tonnes/million cubic metre of gas consumption
LNG:				
Import/Export		1660	-20% to +30%	Tonnes/station
Storage		22	-20% to +30%	Tonnes/station
DISTRIBUTION				
Less than 50% plastic pipelines, or limited or no leak detection and repair programme		2.92	-20% to +120%	Tonnes/million cubic metre of gas consumption
		1.7	-20% to +120%	Tonnes/kilometre of pipeline
Greater than 50% plastic pipelines, leak detection and repair programs are in use		0.62	-20% to +120%	Tonnes/million cubic metre of gas consumption
		0.23	-20% to +120%	Tonnes/kilometre of pipeline
Short term surface storage		5	-50% to +100%	Tonnes/million cubic metre of gas stored
		0.003	+/-100%	Tonnes/million cubic metre of gas consumed
Town gas distribution		0.58	+/-25%	Tonnes/kilometre of pipeline
POST-METER				
Natural gas fuelled vehicles		0.3E-0.3	-50% to +100%	Tonnes/car
Appliances in Commercial and Residential Sector		4E-03	+/-60%	Tonnes/appliance
Leakage Industrial Plants and Power stations		0.4	+/-60%	Tonnes/million cubic meter non-residential and commercial gas consumed
ADDITIONAL				
Ruptures, Accidents, Well Blowouts		??	??	THESE ARE POTENTIAL SUPER-EMITTERS
Abandoned gas wells		??	??	

*Transmission and storage values from US EPA, distribution values from US EPA and German Government (for town gas), post-meter values from Bender and Langer (2012) and IPCC Guidelines (2006).

Source: IPCC (2019). Volume 2, Chapter 4. Tables 4.2.4I, 4.2.4J and 4.2.4K, pp. 4.76-4.77, 4.79 and 4.82.

APPENDIX 4. Methane Emission and Uncertainty Factors for the Oil Supply Chain - Tier 1

Table A4.1: Oil Exploration, Production, Refining, Transport and Abandoned Wells*

SEGMENT		VALUE	UNCERTAINTY FACTOR %	UNITS OF MEASURE
EXPLORATION				
Onshore unconventional without flaring or recovery		6.63	+/-30%	Tonnes/unconventional onshore oil wells drilled in a year without flaring or recovery
		0.46	+/-30%	Tonnes/total unconventional onshore oil well population where exploration occurs without flaring or recovery
		1.64	+/-30%	Tonnes/thousand cubic metres unconventional onshore oil production where exploration occurs without flaring or recovery
Onshore unconventional with flaring or recovery		0.81	+/-30%	Tonnes/unconventional onshore oil wells drilled in a year with flaring or recovery
		0.07	+/-30%	Tonnes/total unconventional onshore oil well population where exploration occurs with flaring or recovery
		0.06	+/-30%	Tonnes/thousand cubic metres unconventional onshore oil production where exploration occurs with flaring or recovery
Onshore conventional		0.53	+/-30%	Tonnes/conventional onshore gas wells drilled in a year
		0.01	+/-30%	Tonnes/total conventional onshore oil wells population
		0.02	+/-30%	Tonnes/thousand cubic metres conventional onshore oil production
PRODUCTION				
Onshore: most activities occurring with higher-emitting technologies and practices		3.43	+/-30%	Tonnes/million cubic metres onshore oil production
		2.35	+/-30%	Tonnes/active oil well
Onshore: most activities occurring with lower-emitting technologies and practices		2.91	+/-30%	Tonnes/million cubic metres onshore oil production
		2.19	+/-30%	Tonnes/active oil well
Onshore: oil sands mining and onshore processing		0.74	+/-30%	Tonnes/thousand cubic metres crude bitumen production from surface mining
Onshore: oil sand upgrading		0.13	-35 to +120%	Tonnes/thousand cubic metres synthetic crude oil production
Offshore		2.46	+/-30%	Tonnes/thousand cubic metres offshore oil production

REFINING	0.03	-50 to +130%	Tonnes/thousand cubic metres of oil refined
TRANSPORT			
Pipelines	0.0054	+/-100%	Tonnes/thousand cubic metres of oil transported by pipeline
Tanker trucks and railcars	0.025	+/-50%	Tonnes/thousand cubic metres of oil transported by truck and railcar
Tanks	0.002	+/-50%	Tonnes/thousand cubic metres of crude oil feel
Loading of offshore production on tanker ships without VRU	0.065	+/-50%	Tonnes/thousand cubic metres of oil loaded onto tanker ship
Loading of offshore production on tanker ships with VRU	0.040	+/-50%	Tonnes/thousand cubic metres of oil loaded onto tanker ship
ABANDONED WELLS**			
Onshore Plugged	2.0E-O5	-87 to +130%	Tonnes of CH4/onshore plugged abandoned well
Onshore Unplugged	8.8E-02	-99 to +150%	Tonnes of CH4/onshore unplugged abandoned well
Onshore: all wells (plugged and unplugged)	1.2E-02	-83 to +124%	Tonnes of CH4/onshore abandoned well
Offshore Plugged	3.5E-07	-87 to +130%	Tonnes of CH4/offshore plugged abandoned well
Offshore Unplugged	1.8E-03	-99 to +150%	Tonnes of CH4/offshore unplugged abandoned well
Offshore: all wells (plugged and unplugged)	2.4E-04	-83 to +124%	Tonnes of CH4/offshore abandoned well

*Exploration values from US EPA, GRI, IPCC (2016); production values from US EPA, GRI, IPCC (2016), Clearstone Engineering, Alberta Energy Regulator, US Bureau of Ocean Energy Management; oil transport values from US EPA; refining values from German government data; abandoned wells from Townsend-Small et al. (2016) from wells across the US.

**Units are mass of emissions per abandoned well.

Source: IPCC (2019), Volume 2, Chapter 4. Tables 4.2.4, 4.2.4A, 4.2.4B, 4.24C and 4,24E pp.4.50-4.63.

APPENDIX 5: Data on Methane Emissions from Underground, Surface and Abandoned[134] Coal Mines

Table A5.1: Estimates of Uncertainty for Underground Mining in Tier 1 and Tier 2 Approaches

Likely uncertainties of coal mine methane Emission factors (Expert judgment - GPG, 2000[1])		
Method	**Mining**	**Post-Mining**
Tier 2	± 50-75%	± 50%
Tier 1	Factor of 2 greater or smaller	Factor of 3 greater or smaller
[1] GPG, 2000 *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories* (2000)		
Likely uncertainties of coal mine carbon dioxide emission factors [2]		
Method	**Mining**	**Post-Mining**
Tier 2	± 50-75%	Not applicable
Tier 1	-50% to +100%	Not applicable
[2] Uncertainties set to be consistent with methane emission factors given that measurement practices are likely to be similar		

Source: IPCC (2019), Volume 2, Chapter 4. p.4.22

Table A5.2: Estimates of Uncertainty for Surface Mining for Tier 1 and Tier 2 Approaches

Likely Uncertainties of Coal Mine Methane Emission Factors for Surface Mining (Expert Judgement[1])		
Method	**Surface**	**Post-Mining**
Tier 2	Factor of 2 greater or lower	± 50%
Tier 1	Factor of 3 greater or lower	Factor of 3 greater or lower
[1] GPG, 2000 - *IPCC Good Practice Guidance* and Uncertainty Management in National Greenhouse Gas Inventories (2000)		
Likely Uncertainties of Coal Mine Carbon Dioxide Emission Factors for Surface Mining [2]		
Method	**Surface**	**Post-Mining**
Tier 2	-50% to +100%	Not applicable
Tier 1	-67% to +200%	Not applicable
[2] Uncertainties set to be consistent with methane emission factors		

Source: IPCC (2019), Volume 2, Chapter 4. p.4.27

[134] Data from abandoned underground mines taken from 2006 but for Tier 1 need to be adjusted by date (IPCC 2019, 4-27-4.28)

Table A5.3: Tier 1 – Abandoned Underground Mines – Example Calculation

	Interval of mine closure					
	1901 – 1925	**1926 – 1950**	**1951 - 1975**	**1976 – 2000**	**2001 – Present**	**Total for inventory year 2005**
Number of mines closed per time band	20	15	10	5	1	
Fraction of gassy mines	0.1	0.5	0.75	1.0	1.0	
Emission factor for Inventory year, 2005 (from Table 4.1.6)	0.256	0.301	0.382	0.601	1.265	
Total emissions (Gg CH_4 per year from Eqn 4.1.10)	0.34	1.51	1.92	2.07	0.85	6.64

Note: Further adjustments by date are required (IPCC 2019, 4-27-4.28)

Source: IPCC (2006), Volume 2, Chapter 4, p. 4.25

APPENDIX 6: The Global Gas Flaring Report, Methodology[135]

"GGDR, in partnership with the United States National Oceanic and Atmospheric Administration (NOAA) and the Colorado School of Mines, has developed global gas flaring estimates based on observations from a satellite launched in 2012. The advanced sensors of this satellite detect the heat emitted by gas flares as infrared emissions at global upstream oil and gas facilities. The Colorado School of Mines and GGFR quantify these infrared emissions and calibrate them using country-level data collected by a third-party data supplier, Cedigaz, to produce robust estimates of global gas flaring volumes.

The satellite data for estimating flare gas volumes is collected by NOAA's satellite mounted Visible Infrared Imaging Radiometer Suite of detectors (VIIRS). VIIRS has multiple, high-resolution detectors which:

- respond only to heat emissions and hence are not affected by sunlight, moonlight, or other light sources;
- respond to wavelengths where emissions from flares are at a maximum; and
- have excellent areal resolution.

The ability of VIIRS to detect only hot sources, such as gas flares, enables flares to be detected automatically with minimal manual intervention. Emissions from non-flare hot sources (e.g. biomass burning) can be removed from the data by selecting only emissions with temperatures above 1100 deg C as other hot sources burn at lower temperatures. Indeed, flares burn hotter than any other terrestrial hot sources, including volcanos. Over the past seven years of operation, VIIRS has automatically detected approximately 16,000 flares annually around the globe."

[135] GGFR (2020), p.6.

APPENDIX 7. Criteria for Calculation of Methane Tracker Data from the IEA Methane Emissions Model[136]

Categories of emission sources and emissions intensities in the United States

Hydrocarbon	Segment	Production Type	Emissions Type	Intensity (mass CH4/mass oil or gas)
Oil	Upstream	Onshore conventional	Vented	0.35%
Oil	Upstream	Onshore conventional	Fugitive	0.03%
Oil	Upstream	Offshore	Vented	0.16%
Oil	Upstream	Offshore	Fugitive	0.01%
Oil	Upstream	Unconventional oil	Vented	0.53%
Oil	Upstream	Unconventional oil	Fugitive	0.04%
Oil	Downstream		Vented	0.003%
Oil	Downstream		Fugitive	0.001%
Oil		Onshore conventional	Incomplete-flare	
Oil		Offshore	Incomplete-flare	
Oil		Unconventional gas	Incomplete-flare	
Gas	Upstream	Onshore conventional	Vented	0.35%
Gas	Upstream	Onshore conventional	Fugitive	0.20%
Gas	Upstream	Offshore	Vented	0.12%
Gas	Upstream	Offshore	Fugitive	0.07%
Gas	Upstream	Unconventional gas	Vented	0.60%
Gas	Upstream	Unconventional gas	Fugitive	0.34%
Gas	Downstream		Vented	0.12%
Gas	Downstream		Fugitive	0.23%

Note: Emission intensities are given here as the energy ratio of tonne of oil-equivalent (toe) methane emitted to tonne of oil equivalent fuel. For natural gas, since this is not 100% methane, ratios differ slightly if given as the volume ratio or mass ratio. For example, the emission intensity for upstream onshore conventional vented emissions in the United States if stated as a volume ratio is 0.36% rather than 0.38% as shown for the energy ratio.

[136] IEA (2020a), Tables 8-10, pp. 63-66.

Scaling factors applied to emission intensities in the United States

Country	Oil and gas production in 2019 mtoe	Oil		Gas	
		Upstream	Downstream	Upstream	Downstream
United States	1404	1.0	1.0	1.0	1.0
Russia	1165	1.9	1.6	1.6	2.0
Saudi Arabia	661	1.5	1.0	1.0	1.5
Canada	422	0.9	0.7	0.7	1.0
Iran	353	2.9	2.8	2.8	2.7
China	335	1.7	1.4	1.4	1.6
Iraq	261	6.0	7.5	7.5	6.2
United Arab Emirates	251	1.6	0.8	0.8	1.5
Qatar	230	1.3	1.0	1.0	1.5
Norway	192	0.1	0.0	0.0	0.0
Kuwait	166	1.8	1.4	1.4	1.7
Brazil	160	1.9	1.7	1.7	1.8
Algeria	148	2.8	2.8	2.8	2.7
Nigeria	138	2.5	2.7	2.7	2.6
Mexico	131	1.6	1.2	1.2	1.6
Kazakhstan	129	2.0	1.4	1.4	1.9
Australia	116	1.0	0.6	0.6	0.8
Indonesia	102	1.7	1.4	1.4	1.6
Malaysia	94	1.2	0.9	0.9	1.1
United Kingdom	88	1.1	0.7	0.7	1.0
Egypt	86	2.2	2.2	2.2	2.1
Oman	83	1.6	1.2	1.2	1.6
Venezuela	80	9.6	11.8	11.8	9.6
Turkmenistan	79	9.1	11.0	11.0	8.9
Angola	76	2.6	3.0	3.0	3.2
United States	1404	1.0	1.0	1.0	1.0
Russia	1165	1.9	1.6	1.6	2.0
Saudi Arabia	661	1.5	1.0	1.0	1.5
Canada	422	0.9	0.7	0.7	1.0
Iran	353	2.9	2.8	2.8	2.7
China	335	1.7	1.4	1.4	1.6
Iraq	261	6.0	7.5	7.5	6.2
United Arab Emirates	251	1.6	0.8	0.8	1.5
Qatar	230	1.3	1.0	1.0	1.5

Equipment-specific emissions sources used in the marginal abatement cost curves

Equipment source	Hydrocarbon	Segment
Large Tanks w/Flares	Oil	Upstream
Large Tanks w/VRU	Oil	Upstream
Large Tanks w/o Control	Oil	Upstream
Small Tanks w/Flares	Oil	Upstream
Small Tanks w/o Flares	Oil	Upstream
Malfunctioning Separator Dump Valves	Oil	Upstream
Pneumatic Devices, High Bleed	Oil	Upstream
Pneumatic Devices, Low Bleed	Oil	Upstream
Pneumatic Devices, Int Bleed	Oil	Upstream
Chemical Injection Pumps	Oil	Upstream
Vessel Blowdowns	Oil	Upstream
Compressor Blowdowns	Oil	Upstream
Compressor Starts	Oil	Upstream
Associated Gas Venting	Oil	Upstream
Well Completion Venting (less HF Completions)	Oil	Upstream
Well Workovers	Oil	Upstream
HF Well Completions, Uncontrolled	Oil	Upstream
HF Well Completions, Controlled	Oil	Upstream
Pipeline Pigging	Oil	Upstream
Tanks	Oil	Downstream
Truck Loading	Oil	Downstream
Marine Loading	Oil	Downstream
Rail Loading	Oil	Downstream
Pump Station Maintenance	Oil	Downstream
Pipeling Pigging	Oil	Downstream
Uncontrolled Blowdowns	Oil	Downstream
Asphalt Blowing	Oil	Downstream
Process Vents	Oil	Downstream
CEMS	Oil	Downstream
Production Compressor Vented	Gas	Upstream
Gas Well Completions without Hydraulic Fracturing	Gas	Upstream
Gas Well Workovers without Hydraulic Fracturing	Gas	Upstream
Hydraulic Fracturing Completions and Workovers that vent	Gas	Upstream
Hydraulic Fracturing Completions and Workovers with RECs	Gas	Upstream
Well Drilling	Gas	Upstream
Pneumatic Device Vents (Low Bleed)	Gas	Upstream
Pneumatic Device Vents (High Bleed)	Gas	Upstream
Pneumatic Device Vents (Intermittent Bleed)	Gas	Upstream
Chemical Injection Pumps	Gas	Upstream
Kimray Pumps	Gas	Upstream

Equipment source	Hydrocarbon	Segment
Dehydrator Vents	Gas	Upstream
Large Tanks w/VRU	Gas	Upstream
Large Tanks w/o Control	Gas	Upstream
Small Tanks w/o Flares	Gas	Upstream
Malfunctioning Separator Dump Valves	Gas	Upstream
Gas Engines	Gas	Upstream
Well Clean Ups (LP Gas Wells) - Vent Using Plungers	Gas	Upstream
Well Clean Ups (LP Gas Wells) - Vent Without Using Plungers	Gas	Upstream
Vessel BD	Gas	Upstream
Pipeline BD	Gas	Upstream
Compressor BD	Gas	Upstream
Compressor Starts	Gas	Upstream
G&B Station Episodic Events	Gas	Upstream
Pressure Relief Valves	Gas	Upstream
Mishaps	Gas	Upstream
Recip. Compressors	Gas	Upstream
Centrifugal Compressors (wet seals)	Gas	Upstream
Centrifugal Compressors (dry seals)	Gas	Upstream
Dehydrators	Gas	Upstream
AGR Vents	Gas	Upstream
Pneumatic Devices	Gas	Upstream
Blowdowns/Venting	Gas	Upstream
Reciprocating Compressor	Gas	Downstream
Centrifugal Compressor (wet seals)	Gas	Downstream
Centrifugal Compressor (dry seals)	Gas	Downstream
Reciprocating Compressor	Gas	Downstream
Dehydrator vents (Transmission)	Gas	Downstream
Dehydrator vents (Storage)	Gas	Downstream
Pneumatic Devices (High Bleed)	Gas	Downstream
Pneumatic Devices (Intermittent Bleed)	Gas	Downstream
Pneumatic Devices (Low Bleed)	Gas	Downstream
Pneumatic Devices (High Bleed)	Gas	Downstream
Pneumatic Devices (Intermittent Bleed)	Gas	Downstream
Pneumatic Devices (Low Bleed)	Gas	Downstream
Pipeline venting	Gas	Downstream
Station Venting Transmission	Gas	Downstream
Station Venting Storage	Gas	Downstream
LNG Reciprocating Compressors Vented	Gas	Downstream
LNG Centrifugal Compressors Vented	Gas	Downstream
LNG Station venting	Gas	Downstream
LNG Reciprocating Compressors Vented	Gas	Downstream
LNG Centrifugal Compressors Vented	Gas	Downstream
LNG Station venting	Gas	Downstream
Pressure Relief Valve Releases	Gas	Downstream
Pipeline Blowdown	Gas	Downstream
Mishaps (Dig-ins)	Gas	Downstream