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The Uncertain Climate Cost of Natural Gas

Assessment of methane leakage discrepancies in Europe, Russia and the US, and implications for sustainability

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Executive Summary

Despite rapid growth in renewable energy worldwide, natural gas finds wide application in different energy sectors such as heating, electricity generation, the petro-chemical industry and transport. Because of its high energy content, one unit of electricity produced through gas combustion releases about half the carbon dioxide in comparison to coal, a factor that often endorses natural gas as a possible 'bridging' fuel toward a low-carbon economy. However, methane itself is a highly potent greenhouse gas, and leakages can occur at many stages of the natural gas supply chain, potentially discrediting methane as a green fuel.

Given the predicted global expansion of gas production and utilisation, the failure to avoid or mitigate methane leakage across the industry will undoubtedly have irreversible repercussions for climate, ruling out natural gas as part of the short-term solution. This forecast expansion is driven by both climate policy as well as increased global access to unconventional reserves and new industrial applications (e.g., Liquefied Natural Gas LNG in transport). Given also the decline in European gas production, reliance on Russian imports is expected to increase in the short to medium term. Germany is Europe's largest consumer of natural gas; however, due to current political and market conditions, coal remains a cheap substitute, thus restraining its share growth. As Germany continues to phase out coal and nuclear as main power sources, however, present energy policies still foresee an increase in gas consumption.

Methane is a short-lived climate pollutant responsible for about one-third of warming due to its powerful, short-term radiative forcing (86 times more than carbon dioxide in a 20-year horizon). Methane can be natural or anthropogenic, with the oil and gas sector contributing significantly to the global emission budget: 11% and 32% of total and anthropogenic sources respectively, according to the Intergovernmental Panel on Climate Change (IPCC). From a comparative analysis of inventories across nations, it appears clear that a lack of understanding of the many sources of methane leakage, and inappropriate measuring across the entire natural gas supply chain, are prevalent among both developed and developing regions, with global losses comparable to German gas consumption.

Here we present a comparison of some countries of interest: The US, Germany, the Netherlands and Russia, with a critical investigation of their national inventories (e.g., data acquisition, monitoring, etc.) and emphasis on the large discrepancies in losses reported across each of the gas segments. Of particular relevance is the case of the US, where estimations of gas leakage rates during upstream operations are considerably higher than European rates. Similar investigations are lacking worldwide, but there is increasing awareness of this issue, with several initiatives originating from international institutions (UNECE), NGOs (CCAC) and gas operators (Marcogaz). To achieve the ambitious international goals outlined in the Paris Climate Agreement, it is crucial for policy makers to take appropriate and timely measures in collaboration with the natural gas industry, to empirically inspect and mitigate methane emissions, whose effect on global temperature is of similar concern to that of carbon dioxide.

Best practices have been demonstrated to be cost-effective and technologically viable in the US, boosting the private sector's engagement and research in the field. Questions remain on the applicability and the

scale of benefits that such measures might bring in other regions, including Europe. Another factor that explains variance and makes comparison challenging is that methane emission standards differ across Europe and are regulated within national schemes. In Russia, uncertainties remain despite several joint campaigns during recent decades to assess the extent of methane losses from national gas infrastructure and operations.

Therefore, countries should factor in all these unknowns when assessing the carbon footprint of their energy systems, in addition to supporting initiatives to investigate and/or implement scientifically validated monitoring systems. If these delicate blind spots on "real emissions" are not addressed quickly and tackled accordingly, sustainability and precautionary principles require that policy evaluations should presume the upper limit of these uncertainty ranges, based on which natural gas cannot be recommended – from a climate perspective – as feedstock of sustainable energy systems nor as a bridging fuel towards a renewables-based energy system.

Contents

Introduction

Natural gas finds wide application in different energy sectors such as heating, electricity generation, the petro-chemical industry and transport. Because of its high energy content, one unit of electricity produced through gas combustion releases about half the carbon dioxide of coal, a factor that often endorses natural gas as a possible 'bridging' fuel toward a low-carbon economy. However, methane itself is a highly potent greenhouse gas, and methane leakages can occur at many stages of the natural gas supply chain, potentially discrediting methane as a green fuel. High leakage rates have tremendous negative impacts on climate because of methane's high warming potential in the short term, which is why preventing methane emissions is a priority. In this critical phase of intensive efforts to reverse GHG emission trends and preserve the environment, timely action to avert gas losses is a prerequisite for final accomplishment. To ensure this, actors in climate and energy policy are required to comply with and actively support actions in this field, with the final aim of determining what contribution gas should play within the international energy transition. If emissions from gas production are ultimately proven to be sufficiently low to endorse natural gas as a mid-term solution together with renewables expansion, such a mix might contribute to slowing climate change and keeping mid-century warming below 2 Celsius. On the other hand, if emissions from gas production cannot be proven to be sufficiently low– or confidently reduced – the future of natural gas in the energy system needs to be severely questioned.

Despite methane's high impact on the climate system, the extent of emissions along the natural gas (and fossil fuels more generally) supply chain is still poorly understood, and very likely underestimated.[1] In support of this, two very recent reports published by the European Commission[2] and Ricardo Energy[3] concluded that natural gas could be more carbon intensive than diesel and kerosene when taking into account methane leaks that are not sufficiently investigated during production, distribution or final utilisation, especially in overseas supply countries. The IEA estimated that the global volume of these emissions in 2013 was equal to annual gas consumption in Germany (ca. 80 bcm).

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[1] Schwietzke, S., Sherwood, O., Bruhwiler, L. M. P., Miller, J. B., Etiope, G., Dlugokencky, E. J., Englund Michel, S., Arling, V. A., Vaughn, B. H., White, J. W. C., Tans, P. P. (2016). Upward revision of global fossil fuel methane emissions based on isotope database. – *Nature, 538*, pp. 88 – 91; Hausmann, P., Sussmann, R., Smale, D. (2016). Contribution of oil and natural gas production to renewed increase in atmospheric methane (2007 – 2014): Top-down estimate from ethane and methane column observations. – *Atmospheric Chemistry and Physics, 16*, pp. 3227–3244, and references therein.

[2] DG Energy, European Commission, (2015). *Study on Actual GHG Data for Diesel, Petrol, Kerosene and Natural Gas, Final Report.* Available at: https://ec.europa.eu/energy/sites/ener/files/documents/Study%20on%20Actual%20GHG%20Data%20Oil%20Gas%20Final%20Report.pdf.

[3] Ricardo Energy and Environment, (2016). *The Role of Natural Gas and Biomethane in the Transport Sector.* Available at: https://www.transportenvironment.org/sites/te/files/publications/2016_02_TE_Natural_Gas_Biomethane_Study_FINAL.pdf.

A significant amount of data on methane emissions has become available in the few past years. The shale gas revolution in the US and its environmental implications triggered deeper investigations of emissions during both conventional and unconventional gas operations,[4] also expanding interest in other regions. The results available today generally show figures two to three times higher than those reported by the EPA in the US. Data inconsistency, poor reporting and measurements, absence of a unified methodology together with outdated emission factors, all contribute to these major revisions and highlight the general tendency to underestimate the real magnitude of leaks. This is also true in Europe, where inventories are mostly supplied by field operators and lack external independent and transparent certification. The accuracy of emission estimates is therefore often unclear. A few international and national projects are underway, and will hopefully pave the way for larger and more comprehensive initiatives in this field. While the tendency to underestimate emissions suggests a potential replication of the US experience here in Europe, the results will naturally rely on factors unique to the European oil and gas (O&G) sector. To this end, the scientific and political community should carefully monitor projects that enlist private sector participation, where conflict of interest and lack of transparency are inherent.

Of special relevance for domestic energy policy and the European *'Energiewende'* more broadly is the assessment of methane leaks from the Russian natural gas industry. As already mentioned, the highest methane emissions are observed in countries with the largest pipeline networks: China, Nigeria, Qatar, Russia and the US. This carries great significance for European energy policy, as Russia remains the most important gas supplier to Europe (37.5% in 2014),[5] and as such warrants closer evaluation of its methane measurement and mitigation activities. Economic interests and mutual dependency between the two regions have therefore to be accounted for when analysing relations in broad terms. On a positive note, numerous joint, international projects have recently been conducted in collaboration with Russian public and private sector actors to identify and reduce emissions from leaks. However, as discussed later in this report, there remains significant potential to curtail emissions at every stage of the supply chain. Given Russia's renewed commitment to climate policy as indicated by recent legislative initiatives, there seems to be a window of opportunity for joint efforts to reduce methane emissions from the Russian gas sector, and thereby the ultimate carbon footprint of European consumers. When widening to other branches of the energy sector, large volumes of methane are also associated with the Russian oil industry, as further elaborated in the report. Despite a prosperous oil industry that is also the cause of additional GHG emissions, this report will mainly focus on the gas sector.

In a world where renewables are quickly taking over energy production, natural gas must prove its green credentials before being politically favoured over coal, which is currently cheaper. Engagement and constructive participation among all sectors is pivotal to ensure that natural gas benefits are visible and viable before making crucial decisions in the energy sector. Improvement of methane measurement and mitigation activities would not only help to determine the appropriate role of natural gas in Europe's energy transition, but could additionally serve as a political tool to raise the saliency of this issue at the global level. In the framework of the COP21 and COP22 negotiations, several countries expressed interest in reducing methane emissions from O&G systems through specific national actions. Close cooperation between the US, Russia and the EU could prove promising to further support and push forward actions within the G20 and the upcoming international meetings.

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[4] IASS (2015). *Shale Gas and Fracking in Europe. – Fact Sheet 1/2015.*

[5] Eurostat (2016). *Energy Production and Imports, EU-28.* Available at: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_production_and_imports#Imports; 13th *EU-Russia Joint Energy Report* (2014), p. 2. Available at: http://www.gosbook.ru/document/83249/83290/preview.

1. Natural gas in the European and German energy transition

Currently, natural gas plays a significant role in the European and German energy mix. Its 2014 share in primary energy consumption amounted to 21.3% in the EU-28[6] and 20.5% in Germany.[7] According to the German Federal Ministry for Economic Affairs and Energy (BMWi), natural gas should remain an important national source of energy in the coming decades,[8] despite its gradual decrease in parallel to a rapid expansion of renewable alternatives. Would this scenario remain the same if methane leaks were properly investigated? Currently, natural gas is widely deployed in electricity generation and heating, and also has important applications as a raw material in the chemical industry (Fig. 1). Furthermore, technologies to reduce GHG emissions in the transport sector via gas-powered engines with minor or zero carbon emissions are also under development (e.g., methane cracking).[9]

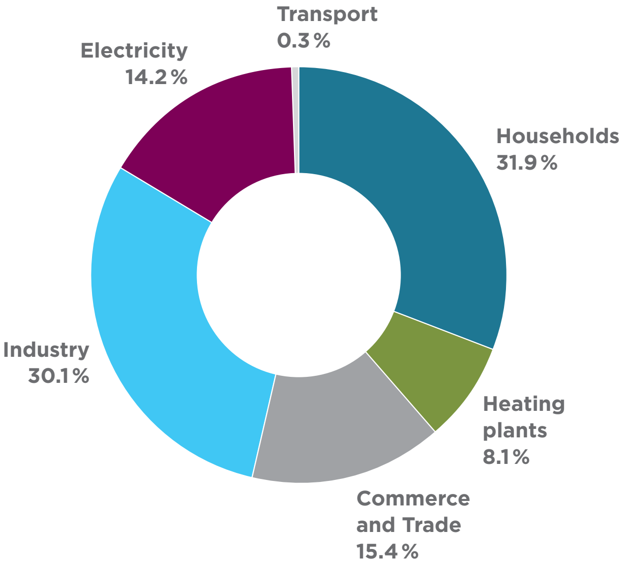

Figure 1: Gas consumption in Germany by sector in 2015.

Source: Exxon Mobil.

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[6] Eurogas (2014). *EU Primary Energy Consumption.* Available at: http://www.eurogas.org/uploads/2016/flipbook/statistical-report-2015/index.html#p=4. Last accessed on 20.12.2016.

[7] BMWi (2016). *Energiedaten: Gesamtausgabe.* Available at: https://www.bmwi.de/BMWi/Redaktion/PDF/E/energiestatistiken-grafiken,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf. Last accessed on 20.12.2016.

[8] BMWi (2016). *Erdgasversorgung in Deutschland.* Available at: http://www.bmwi.de/DE/Themen/Energie/Konventionelle-Energietraeger/gas.html. Last accessed on 20.12.2016.

[9] IASS, *Combustion of Methane Without CO_2 Emissions.* Available at: http://www.iass-potsdam.de/en/research/energy/systems-in-transition/combustion-methane-without-co2. Last accessed on 20.12.2016.

The EU and German commitment to a more sustainable and climate-friendly energy system implies a transition from fossil fuels to renewable energy sources while increasing energy efficiency standards. The new energy system in Germany and Europe will be shaped by increasing competition among fossil fuels and with renewable energy sources. After a first period characterised by feed-in tariffs in Germany, market-based economic competition will dominate the power supply system, according to the current situation. In this context, a vision of the future energy mix, specifically on the future role of gas, needs to be comprehensively analysed. The place and role of each energy carrier in the economy largely depends on policy preferences and cost competitiveness vis-à-vis other energy sources. The main challenges facing the energy transition in Europe and Germany involve finding the right balance, and avoiding disruption in the financial and energy sectors and economic imbalances.

1.1 The power and heating sectors

Renewable energies (RE) in the electricity sector have experienced remarkable success in Germany. The German Renewable Energy Act (EEG), through its investment system, has successfully integrated RE in the markets and stimulated technological innovation in this field. This is evident from the share of renewable energy in electricity generation in Germany, which increased substantially, from 16.6 % in 2010 to 32.5 % in 2015 while the share of natural gas decreased from 14.1 % to 8.8 % during the same period.[10] This drop in the use of natural gas can be attributed to low coal and CO_2 prices, with the result that even some of the newest gas-fired power plants were unprofitable against coal and had to be shut down (e.g., *Irsching* blocks 4 and 5 by E·ON).[11] Additionally, the German Government's recent decision to reform the energy market by introducing capacity reserve instead of the capacity market has made gas generation less competitive than coal.[12] At the current stage, only combined heat and power (CHP) plants will receive temporary support because of their high efficiency potential. In this scenario, gas-fired power plants will mainly serve as back-up capacity to support intermittent solar and wind.

In the heating sector, the use of renewable energy is also increasing in Germany, albeit at a slower pace. In the period from 2010 to 2014, the share of renewable-based heat consumption in Germany increased from 11.1 % to 12.2 %.[13] Overall, renewables accounted for 15 % of German household heat production in 2015, while natural gas and oil accounted for 44 % and 26 % respectively.[14] However, as a consequence of additional energy efficiency measures, heat consumption is expected to decrease substantially in the medium to long term (by about 20 % in 2040), while the share of renewables used in this area will continue to rise.[15] Recent changes to the legislation on CHP incentivise replacement of coal with natural gas, which might expand its share in the heating sector.

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[10] Agora Energiewende, available at: https://www.agora-energiewende.de/en/press/agoranews/news-detail/news/2015-was-a-record-year-for-renewable-energies-power-production-and-power-exports-in-germany-1/News/detail/. Last accessed on 20.12.2016.

[11] Irsching Power Plant has five blocks in total. Block 1 was decommissioned in 2006 and Block 2 in 2012. Block 3 is used in exceptional circumstances to help provide grid stability. Finally, blocks 4 and 5 could be closed after March 2016 when the contract with network operator to provide grid stability expires. Bloomberg, available at: http://www.bloomberg.com/news/articles/2015-03-30/eon-files-to-close-two-unprofitable-irsching-gas-power-plants. Last accessed on 20.12.2016.

[12] Total marginal costs (basically fuel and emission allowance costs) are cheaper for coal production, since low-emission allowances do not offset the cheap price of coal. Although gas-fired power plant operators and their associations hoped for the German Government to set a capacity market able to support gas-fired power generation, the white paper "An Electricity Market for Germany's Energy Transition" (July 2015) clearly stated that the electricity price is to be defined on the principle of "free formation of prices". With the exception of CHP plants, gas-fired power plants will therefore continue to be unprofitable.

[13] BMWi (2015). *Development of Renewable Energy Sources in Germany in 2014.* Available at: http://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/development-of-renewable-energy-sources-in-germany-2014.pdf?__blob=publicationFile&v=6. Last accessed on 20.12.2016.

[14] ExxonMobil, available at: http://cdn.exxonmobil.com/-/media/germany/files/energieprognose/energiegrognose2016.pdf. Last accessed on 27.01.2016.

[15] Ibid.

1.2 The transport sector

To reduce European dependence on oil in the transport sector and to curb CO_2 emissions, the EU adopted several key directives on alternative fuel infrastructure, such as the Clean Power for Transport Package[16] and the EU Sulfur Directive.[17] In addition, the MARPOL Convention[18] is currently being implemented in the Baltic Sea area. The final directive, which was adopted by the European Parliament and Council in 2014, requires member states to develop national plans for the implementation of alternative fuels, in particular liquefied and compressed natural gas (LNG and CNG), in the freight and automotive sectors. This decision was based on the conclusion that natural gas performs better than diesel and kerosene in terms of atmospheric emissions. Indeed, comparison between LNG and CNG with diesel, of emissions arising solely from combustion, shows that both had a smaller environmental impact than the widely used diesel. The combustion of LNG produces no particulate matter (PM), about 90% less sulphur oxides (SOx), emits 80% to 90% less nitrogen oxides (NO_x) and 20% to 25% less CO_2 compared to conventional heavy- and low-sulphur oil fuels.[19] Moreover, gas-fired vehicles cause less noise pollution than diesel engines, which has additional direct benefits for quality of life.

1.3 Other applications

Natural gas is widely used as raw material in the chemical industry, particularly in the production of ethylene used to manufacture the majority of plastic components and basic commodities. At a glance into the future, the natural gas grid could be suitable for storing and transporting biogas and synthetic gas as a clean alternative (e.g., from technologies referred to as power-to-gas).

As a direct consequence of conservative assumptions regarding the extent of methane leaks, future projections assume that natural gas will continue to represent an important energy source in the short- and medium term, while its total consumption is likely to decrease beyond that. Questions remain on its share and lifetime in the energy mix, especially from the perspective of wider climate concerns. In fact, there is still active debate in many countries, on the role of gas as a potential transition fuel, and apparently regional settings are crucial in framing this issue.[20] For this reason, measuring campaigns must be extended alongside an urgent and deep analysis of emission mitigation options. Should these investigations confirm the feared inaccuracies mentioned here, the role of natural gas in the future energy mix should be reassessed.

[16] European Commission, available at: http://ec.europa.eu/transport/themes/urban/cpt/index_en.htm. Last accessed on 20.12.2016.

[17] European Commission, available at: http://ec.europa.eu/environment/air/transport/ships.htm. Last accessed on 20.12.2016.

[18] International Maritime Organization (2016). *International Convention for the Prevention of Pollution from Ships (MARPOL)*. Available at: http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx. Last accessed on 20.12.2016.

[19] European Commission (2016). *Liquified Natural Gas: An Attractive Fuel Solution for Shipping*. Available at: https://lngforshipping.eu/wp-content/uploads/2015/02/Brochure-LNG-def.pdf. Last accessed on 20.12.2016.

[20] UK Energy Research Centre (2016). *The Future Role of Natural Gas in the UK*. Available at: https://www.wbs.ac.uk/wbs2012/assets/PDF/downloads/press/gas-report.pdf. Last accessed on 20.12.2016.

2. Why methane leaks matter

When accounting for carbon dioxide and other air pollutants emitted during combustion, natural gas utilisation provides tangible environmental advantages. However, even minor intrinsic (fugitive) or operational (venting) methane losses occurring on the path from production sites to consumers would both negate these benefits, due to methane's potent warming potential and ultimate contribution to climate change. Studies of the US energy system showed that if methane leakage accounts for more than ~2.7% of the total gas burned, the advantages of natural gas over coal are lost in the immediate term.[21] To thoroughly understand this tangible threat and its changing contribution through time, we briefly refer to the concept of Global Warming Potential (GWP).

As a GHG, methane is far more potent than carbon dioxide. Once emitted to the atmosphere it persists for approximately a decade, then decays to form additional CO_2.[22] This is mostly taken up by the ocean and terrestrial biosphere, while the remaining proportion persists for centuries in the atmosphere. The net result is a dynamic curve with a temporal component, describing how much impact methane will have over time, relative to the net radiative forcing ("heating" effect on the atmosphere). This relationship, also called GWP, shows that on a kg per kg basis, methane is 86 times stronger than carbon dioxide over a 20-year period and 34 times stronger over a 100-year period, according to IPCC estimates.[23] This means that the cumulative warming effect of methane absorbing incoming solar radiation over 20 years since its emission, directly or indirectly (e.g., as a precursor or other air pollutants), is in total 86 times more than that associated with the same amount of CO_2 over the same period of time. Although methane has a lifetime of only 12 years – so that only 2% of it will still be present in the atmosphere after 50 years from its emission – it is much more effective at trapping heat than carbon dioxide. Therefore, its short-term impact is large enough to offset its rapid disappearance. Translated into practical terms, even small volumes of natural gas escaping into the atmosphere can substantially increase the overall carbon footprint of this fossil fuel. Figure 2 shows the different shares of heat produced by methane and CO_2 when comparing 20-year and 100-year timespans.

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[21] Hamburg, S., available at: http://blogs.edf.org/energyexchange/2013/11/05/methane-a-key-to-dealing-with-carbon-pollution/?_ga=1.202112914.2055223472.1399629208. Last accessed on 20.12.2016.

[22] Alvarez, R., Pacala, S. W., Winebrake, J. J., Chameides, W. L., Hamburg, S. P., (2012). Greater focus needed on methane leakage from natural gas infrastructure. – *PNAS, 109*(17), pp. 6435–6440; Edwards, M. R., Trancik, J. E. (2014). Climate impacts of energy technologies depend on emissions timing. – *Nature Climate Change*, 4(5), pp. 347–352.

[23] IPCC (2014). *Fifth Assessment Report* (AR5). Available at: http://www.ipcc.ch/report/ar5/wg1/. Last accessed on 20.12.2016.

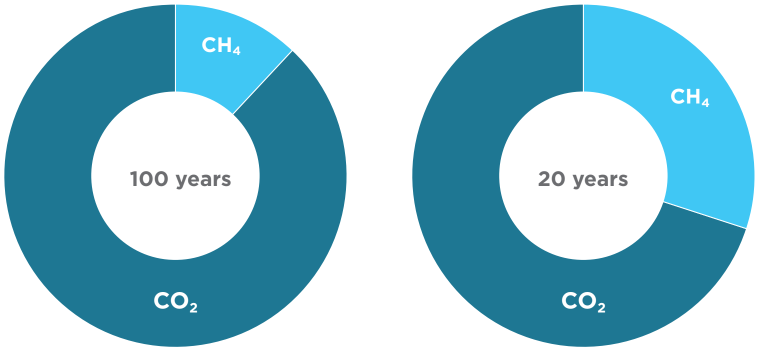

Figure 2: Final warming effect of methane and carbon dioxide GWP in Europe. Comparison between 100-year and 20-year horizons.

Source: European Environmental Agency (EEA).

Although the methane "warming input" is largely concentrated within a short time span, the 100-year horizon GWP is widely accepted as the standard approach for calculating its CO_2-equivalence, similarly to other long-lived non-CO_2 GHGs. However, the 20-year GWP is highly relevant for assessing the implications of methane for short-term tipping points in the climate system, while the 100-years GWP is meaningful when addressing long-term atmospheric carbon budget and temperature increase. Consequently, urgent reductions in methane emissions are vital to avoid crossing tipping points that are crucial to the chances of keeping mid-century warming below 2 Celsius. Accordingly, the IEA states that *"[methane reduction] is no substitute for long-term measures to cut CO_2 emissions, but the potential to slow the near-term rate of warming"*.[24] Similarly, the IPCC 2014 report, based on comparison of the GWP of different anthropogenic emissions over 10-, 20- and 100-year timescales, underlined that global methane emissions slightly outweighed CO_2 emissions over a 10-year period, with significant repercussions for temperatures (Fig. 3).

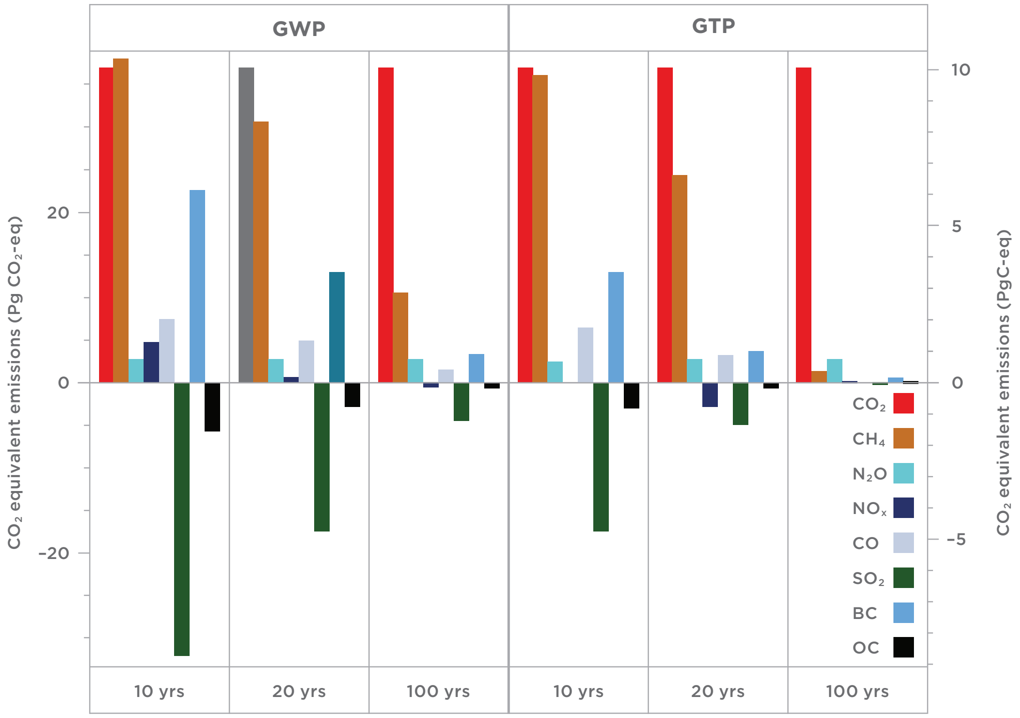

Figure 3: Global anthropogenic emissions weighted by Global Warming Potential (GWP) and Global Temperature Potential (GTP).

Source: IPCC Report 2013, Ar5, Wg.1, fig. 8 – 32.

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[24] IEA (2015). *Energy and Climate Change: World Energy Outlook Special Report*, p. 95. Available at: https://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf. Last accessed on 20.12.2016.

3. Methane emissions and international efforts to mitigate climate change

Recent scientific findings emphasise the importance of methane emissions compared to other climate pollutants such as carbon dioxide and black carbon. An increased awareness of the benefits achievable by minimising these emissions is also tangible among research and governmental institutions. The climate model published in 2012 by the NASA Goddard Institute for Space Studies concluded that reduction of methane emissions and black carbon *"allows a rapid climate response to emissions reductions" and that "the CO_2 emissions reductions hardly affect temperatures before 2040"*.[25] As shown in Figure 4, if methane emissions and black carbon are not reduced in the near term, global temperature will increase by 1.5 degrees by about 2030 and 2 degrees by 2045 regardless of whether carbon dioxide emissions are reduced. Black carbon, defined as light-absorbing carbonaceous aerosol generated during combustion, is also produced in large quantities by flaring activities in the O&G sector.

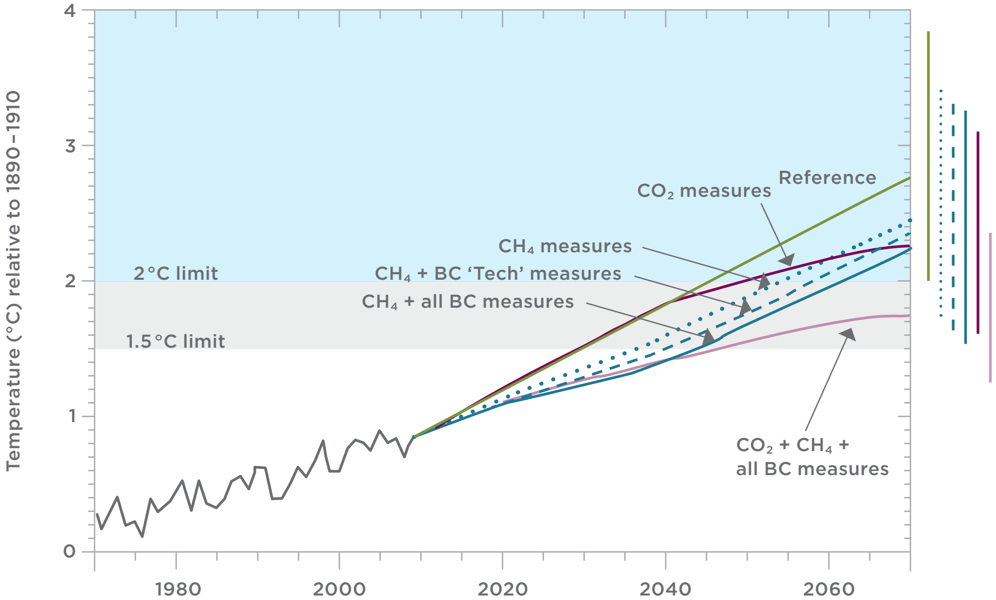

Figure 4: Impacts of different mitigation measures on global temperature.

Source: Shindell et al. 2012.[26] Reprinted with permission from AAAS.

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[25] Shindell, D., Kuylenstierna, J. C.I., Faluvegi, G., Milly, G., Emberson, L., Hicks, K., Vignati, E., Van Dingenen, R., Janssens-Maenhout, G., Raes, F., Pozzoli, L., Amann, M., Klimont, Z., Kupiainen, K., Höglund-Isaksson, L., Anenberg, S. C., Muller, N., Schwartz, J., Streets, D., Ramanathan, V., Oanh, N. T. K., Williams, M., Demkine, V., Fowler, D. (2012). Simultaneously mitigating near-term climate change and improving human health and food security. – *Science, 335*(6065), pp. 183–189.

The United Nations Environment Programme (UNEP) concluded that *"reductions in CH_4 emissions are virtually certain to mitigate near-term warming. The effects of black carbon measures have a much larger uncertainty"*.[27] The same report also gave directions on mitigation strategies: *"most of the measures targeted at CH_4 involve action by large international and national energy companies (coal mining, oil and gas production), municipalities (treatment of waste and wastewater), and the agricultural sector*[28] *(rice fields)"*.[29] The World Energy Outlook 2015 as well as Energy and Climate Change Report[30] by the IEA suggests that reducing methane emissions from the O&G sectors is one of five key measures that can help to ensure a peak in global GHG emissions by 2020 and thus provide a reasonable chance of limiting global warming to 2 Celsius. Regarding actions in the O&G sector, the IEA underlines that *"upstream oil and gas methane reductions could yield 15% of the reductions needed to deliver such an early peak in emissions, an amount similar to that which would be realised through incremental investments in renewables"*.[31]

Interest in the topic of methane emissions by governments, EU institutions and the general public has increased considerably in the past several years, mostly due to extensive measurements and studies in the US, which revealed that methane emissions from the US gas sector were likely higher than previously estimated.[32] Global methane emissions from the O&G sectors are estimated at 55 million tonnes per year against a total of 550 million tonnes, which is equal to 80 bcm of vented gas.[33] In 2009 a group of researchers at Cornell University began to explore the carbon footprint of natural gas. Their first paper, published in 2011, concluded that methane emissions from conventional and unconventional gas were likely two- to three-fold higher than reported by the US EPA. Since then, an extensive debate has been triggered, with a new research initiative aimed to update inventories and mobilise political action. As a result, the EPA considerably revised its emission factors and found that the leakage rate for upstream conventional gas substantially increased, as reported in Figure 5. Balcombe et al. (2016)[34] claim that most leaks occur during well completion (pre-production stage), liquids unloadings and workovers (extraction stage), and transmission, storage and distribution stages. This study is based on data from both unconventional and conventional wells. Forthcoming investigations by the Environmental Defence Fund (EDF) and other sources will very likely further revise upwards the EPA estimates. Nevertheless, compared with methane emissions in 1990, total magnitude decreased from 1.9% to 1.1% in 2011 according to revised EPA inventories. At the European level, the 2015 report by the European Commission called attention to the adverse impacts of gas principal actors. This investigation, which compares the carbon footprint of different European fossil fuel supplies, concluded that GHG emissions in the natural gas sector were slightly higher than for other fossil fuels (diesel, petrol, kerosene).[35] In response to that study, several members of the European Associations of Natural Gas sent a joint letter admitting existing data gaps in emission inventories and also expressing a willingness to cooperate on this issue.

[26] Ibid.

[27] UNEP (2011). *Integrated Assessment of Black Carbon and Tropospheric Ozone*, p. 172. Available at: http://www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf. Last accessed on: 20.12.2016.

[28] Ibid.

[29] Saunois, M., Jackson, R. B., Bosquet, P., Poulter, B., Canadell, J. G. (2016). The growing role of methane in anthropogenic climate change. – *Environmental Research Letters, 11* (12).

[30] See reference: 27.

[31] See reference: 24.

[32] Rhodium Group (2015). *Untapped Potential: Reducing Global Methane Emissions from Oil and Natural Gas Systems.* Available at: https://www.edf.org/sites/default/files/content/rhg_untappedpotential_april2015.pdf. Last accessed on 20.12.2016.

[33] See reference: 27, p. 212.

[34] Balcombe, P., Anderson, K., Speirs, J., Brandon, N., Hawkes, A. (2016). The natural gas supply chain: The importance of methane and carbon dioxide emissions. – *Sustainable Chemistry and Engineering*, in press. DOI: 10.1021/acssuschemeng.6b00144.

[35] See reference: 2.

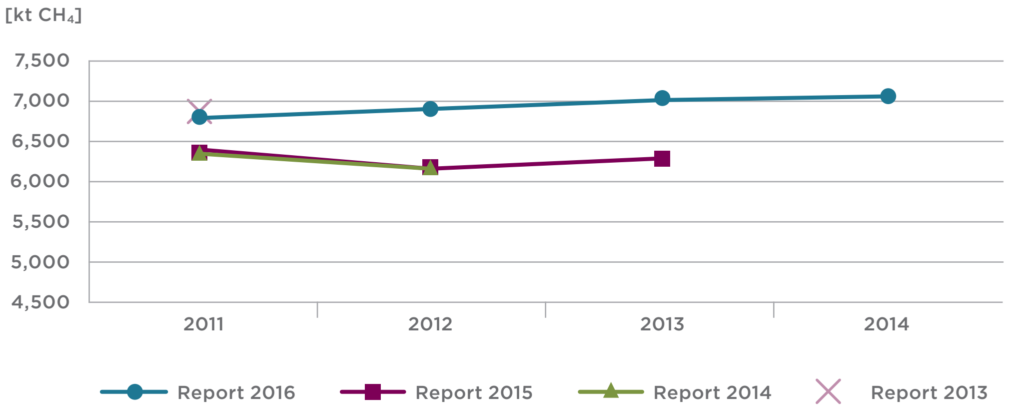

Figure 5: Methane emissions (kt) from the US Natural Gas system.

Source: US GHG Inventory report submitted to UNFCCC.

The largest O&G pipeline networks are the highest methane emitters, with China, Nigeria, Qatar, Russia and the US contributing the highest emissions levels.[36] It is therefore crucial that these large regions take quick mitigation actions. Due to this high magnitude of methane emissions, the United States and Russia have attempted to assess the extent of methane leaks and to implement appropriate measures for reducing natural gas releases into the atmosphere.[37] Within the framework of COP21 and COP22 negotiations, several countries expressed interest in reducing methane emissions from natural gas systems and establishing Intended Nationally Determined Contributions (INDCs). Independently of the Paris Agreement, the US (and recently Canada[38]) agreed to cut emissions of methane from the O&G sector by 40–45% below 2012 levels by 2025, a decision strongly supported by the Obama Administration after the economic advantages of these measures were proven viable.[39] Mexico, Gabon and Indonesia have also pledged action in this area.

It is important at this stage for the scientific sectors to continue underlining the urgency of targeted actions in this field, so as to encourage national political agendas to incorporate mitigation measures into future strategic activities. This might ultimately maximise the benefits of natural gas, especially in regions where environmental standards have large margins for improvement. In parallel, it is crucial to assess the economic viability of methane reduction strategies, as well as the political willingness to strictly regulate the O&G sector and its emissions, where required. Fragile equilibria between politics and large business enterprises are by nature resistant to transitions, particularly when jobs and revenues are at risk. Negotiations and strategies to overcome these limitations are region-specific, so that a "one-size-fits-all" solution is missing. The new environmental standards enacted by the US presidency, and the ways in which the business sector barely complies with their requirements, provides a good example of practical hurdles encountered on the ground. These challenges are also evident within leak-reduction programmes, as such the Natural Gas STAR Methane Challenge Program launched by the EPA in March 2016.[40] We also expect similar burdens in Europe, if on one side environmental standards are widely accepted in the business field whereas on the other hand the drying up of European conventional gas basins is of relevant concern for companies. Other obstacles of different nature are expected elsewhere, and present large uncertainties for a rapid and straightforward solution if/when the methane issue is confirmed, further postponing a solution to the role of natural gas in the energy transition.

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[36] See reference: 24.

[37] EDF, available at: https://www.edf.org/media/us-canada-pact-step-toward-future-safe-climate-change-edf-president-fred-krupp.

[38] Ibid.

[39] Reuters, available at: http://in.reuters.com/article/us-canada-agree-to-cut-methane-emissions-idINL1N16I0HL. Last accessed on 20.12.2016.

[40] EPA, Natural Gas STAR Methane Challenge Program, available at: https://www.epa.gov/natural-gas-star-program/natural-gas-star-methane-challenge-program.

4. Current status of methane emissions from the gas sector

At the global scale, self-reported methane emissions from the O&G sector present significant discrepancies. The topic of methane emissions from the natural gas supply chain has recently been widely discussed in the US and Russia, while little attention has been paid to European gas pipeline systems to date. Methane emissions in Europe and Germany often rely on conservative assumptions and lack accurate updates, as elaborated later in the report.

4.1 Worldwide methane emissions from the oil and gas sectors

Whereas in some countries the issue of methane emissions has already been recognised as an important problem to be addressed, the situation in many other key countries remains very unclear, particularly in China, the Middle Eastern and African countries. Amongst the 20 largest natural gas producers, the US, Canada and Russia report gas leakages between 1% and 2%, while other countries such as Qatar, Saudi Arabia, China and Norway report essentially no emissions. Even larger disparities are reported for the upstream O&G leakage rate, as elaborated later in the report.[41] At a global scale, all IPCC reference studies agree on worldwide total methane emissions between 450 and 550 million tonnes, and an O&G sector share of between 9% and 12% (see Fig. 6a).

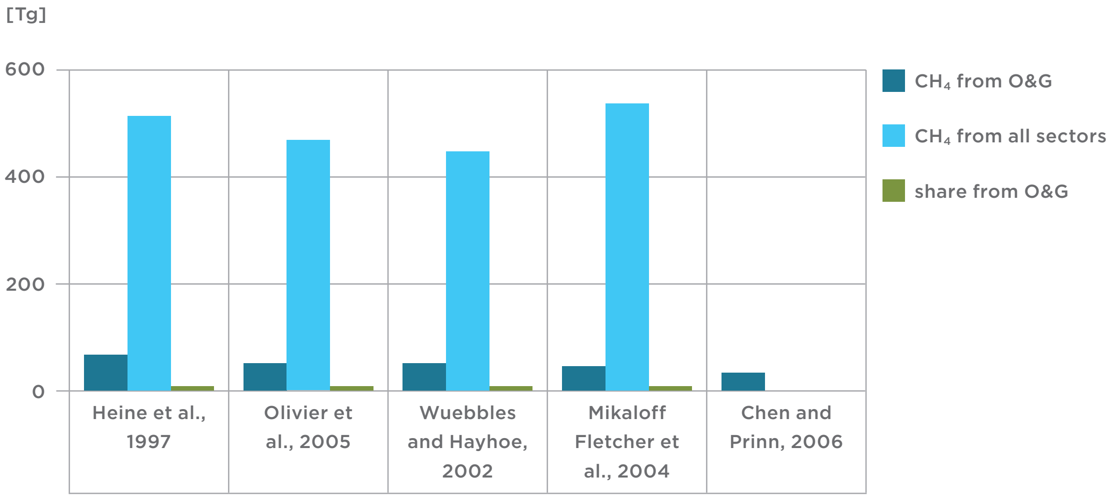

Figure 6a: Global O&G methane emissions share.

Source: IPCC.[42]

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[41] See reference 3.

[42] Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B.., Tignor, M. and and Miller, H. L. (2007). *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

A regional breakdown of methane emissions in the energy sector shows instead large offsets: methane emissions account for 8% of the total in Europe, compared with 33% in the US. As a rule of thumb, emissions are higher in countries with larger production volumes and transmission capacities, in both absolute and relative numbers (Fig. 6b). To put that into context, production of crude oil and natural gas from shale in the US has experienced a remarkable increase in recent years, which made the US a self-sufficient region. Gas production approximately seven times that of Europe might explain the disparity, although leakage rates in these two regions are significantly different (see the later discussion). Assuming comparable pro-capita gas consumption and environmental standards, we can speculate that the production sector is widely responsible for this large difference, assuming that other sectors are not major emission sources (as confirmed in Fig. 9).

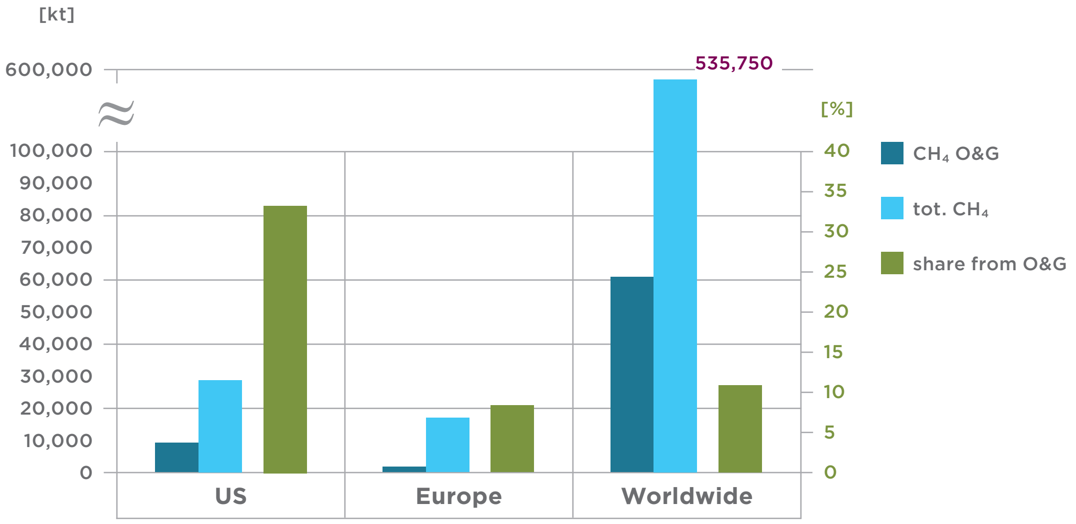

Figure 6b: Total methane emissions and share from the O&G sector in different regions. The share in [%] is reported on the right axis.

Source: IPCC, EPA, EEA, own calculations.

4.2 Emissions comparison: Germany, Netherlands, US and Russia

A breakdown of GHG emissions in Europe for 2014, presented by the European Environmental Agency (EEA) and based on aggregated values from the UNFCCC databases and the EU Greenhouse Gas Monitoring Mechanisms, depicts the energy sector as the second largest methane emission source after agriculture in Germany, and the third largest in Europe, after agriculture and waste management (Fig. 7).

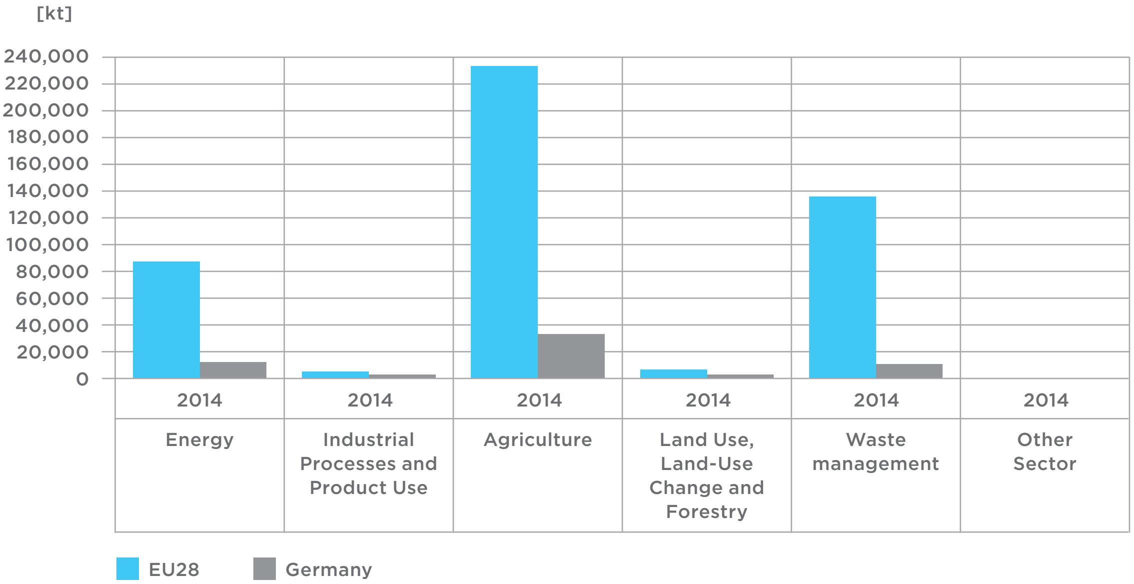

Figure 7a: Methane emissions by sector in Europe and Germany in kt of CO_2.

Source: European Environment Agency (EEA).

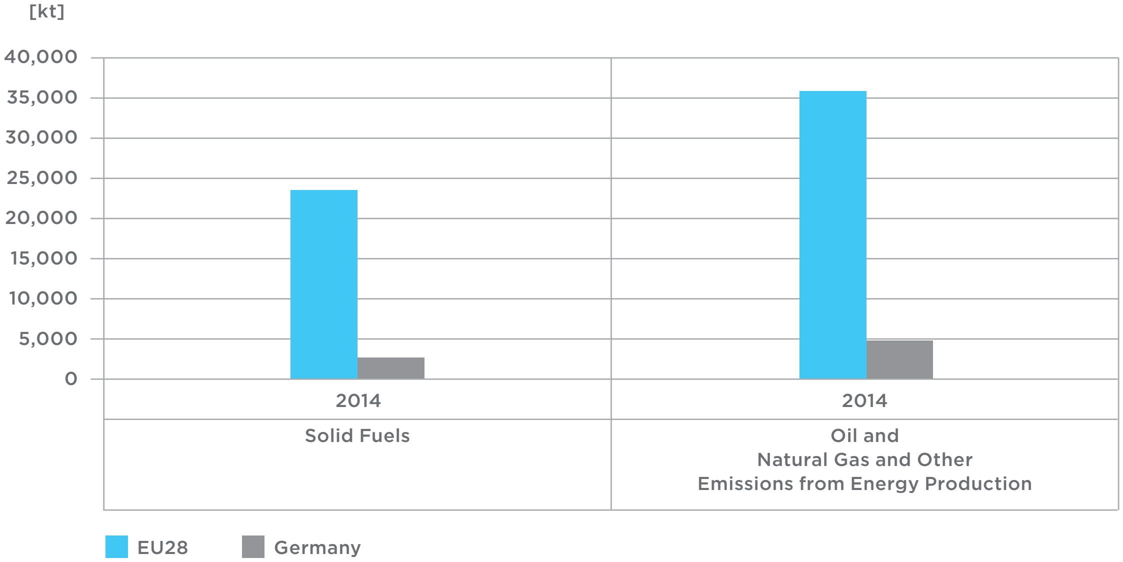

Figure 7b: Methane emissions from solid fuels and O&G in Europe and Germany in kt of CO_2eq.

Source: European Environment Agency (EEA).

In 2014, total methane emissions from the O&G sector in Germany accounted for 5 Mt (CO_2-equivalent, on a 100-year horizon) against 2.5 Mt from solid fuels (mostly coal) (Fig. 7).[43] The German UNFCCC inventory 2016 (reporting latest emissions for the year 2014) reveals that the distribution segment is responsible for more than half of the total, and together with transmission lines accounts for almost 90% (Fig. 8a). Production would contribute only 1% of total emissions. The category "others" in the figure includes emissions at sites of natural gas use, while emissions from venting and flaring are aggregated together with oil production (2.4 million tons produced in 2014).[44] Despite the small amount of gas produced and processed domestically (i.e., 9.2 bcm in 2014)[45] these estimates can be considered conservative, as elaborated later in the report.

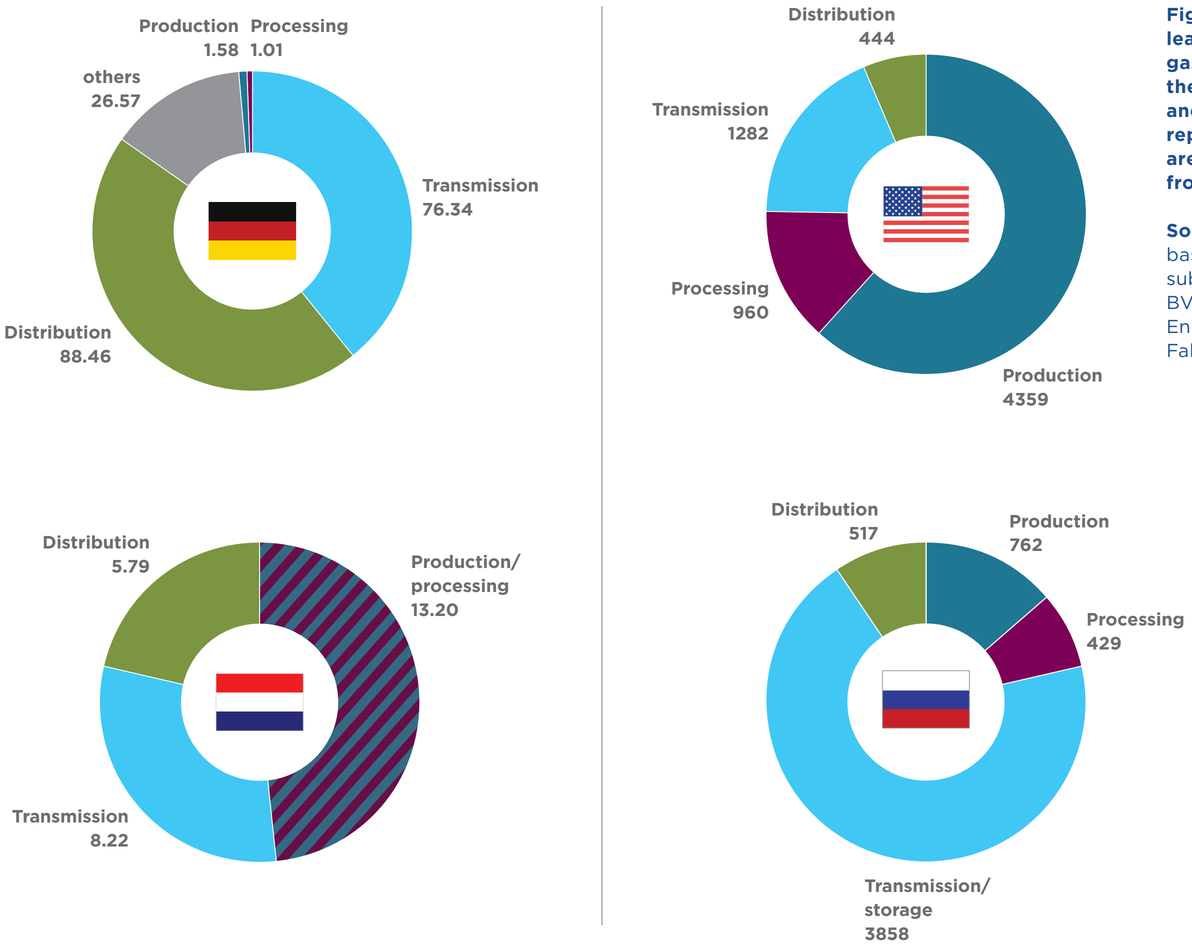

Figure 8: Methane leakages from natural gas system in Germany, the Netherlands, Russia and US, 2014. The numbers reported in the figure are kt of total methane from each sector.

Source: own calculations, based on UNFCCC, submission 2016, EIA, BVEG (former WEG), Energie Daten und Fakten (BMWi), NLOG.

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[43] EEA (2016), available at: http://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer. Last accessed on 20.12.2016.

[44] Wirtschaftsverband Erdö- und Erdgasgewinnung e.V. (2015). Jahresbericht 2014/2015 – Zahlen und Fakten. Available at: http://www.bveg.de/Medien/Publikationen/Jahresberichte. Last accessed on 20.12.2016.

[45] Ibid.

The US presents a marked inversion of main emission sources: production and processing represent three quarters of total emissions, while distribution would only be responsible for approximately 5%. In Russia, transmission and storage accounted for the largest part of methane emissions, followed by production. Intermediate values characterise the Netherlands, where production and processing together account for about 50% of total emissions, with the remainder equally distributed between transmission and distribution. The fact that the US and Russia are gas self-sufficient while Germany only produced about 10% of national need can partially explain this offset: normalising gas outputs shows that the production sector in Germany would still be responsible for a total gas release thirty times less than claimed in the US (Fig. 9). To support the lack of correlation between gas production volumes and leakage, we examine the examples of Norway and the Netherlands: Both report methane emissions significantly lower than those of Germany (almost none in Norway) despite the very large volumes of natural gas produced. Total methane emissions from the natural gas sector in 2014 accounted for 2.8 kt in Norway, 27.2 kt in the Netherlands and 194 kt in Germany.[46] Robust environmental standards active in Norway and the Netherlands, or a lack of accurate measurements, may both explain this discrepancy. It is evident that methane emissions are concentrated at different stages of the gas chain according to the country: production and transmission are characterised by high magnitude of emissions in absolute and relative terms in the US, but that is not replicated in Russia. The same sectors are instead characterised by low emissions in absolute and relative terms in Germany, and by high emissions in relative terms but low emissions in absolute terms in the Netherlands. It is challenging to explain this large variance through practices or legislative regimes.

Similar incongruities emerge when analysing methane leakage rates for Germany, the Netherlands, Russia and the US in different natural gas segments of the natural gas supply chain (Fig. 9). It is important to mention that the sourcing inventories present different estimation procedures, elaborations and reporting units that inevitably impose limitations in the following quantitative analyses. For example, activity data units are sometimes different and therefore comparisons are challenging (e.g., gCH_4 loss along the pipeline can be reported as: i. volume of gas flowing; ii. pipeline extension units), according to the Tier approach used for that specific parameter. Nevertheless, it is still possible to identify and highlight significant discrepancies that are worth discussing. For example, it is notable that the production segment (without processing) in the US is responsible for a loss of 0.68%[47] of the total natural gas output, which also represents 62% of total methane losses from the natural gas supply chain. This is notably higher than Russian figures, where production would only leak 0.2% of total volumes. Emissions from the same sector in Germany would instead be negligible, according to the data source: irrelevant for exploration and around 0.025% for production (note here that emissions from O&G sectors are aggregated). The situation is similar in the Netherlands, where leaks aggregated from gas production and processing amount to only 0.029% of total natural gas produced.

In the transmission system, the Netherlands appears to emit about one tenth that of Germany (where the grid is more extended and hosts higher flows due to its geographic position). The more extensive German network fairly translates to more sources of loss. Additionally, other equipment on transmission lines, such as high-pressure compressor stations, sliding sleeves and other systems to measure and regulate gas pressure have recently been evaluated and asso-

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[46] *UNFCCC, Common Reporting Format* (2016). Available at: http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php. Last accessed on 20.12.2016.

[47] Own calculations. Data sources: UNFCCC, US National Inventory Report (2016); Energy Information Administration. Data for 2014.

ciated emissions have been incorporated within the UNFCCC inventory. Specifically regarding sliding sleeves, emission factors are considered conservative by the same authors because they are taken from dated studies on long-distance transmission pipelines in Russia. In the Netherlands, instead, measurements through LDAR devices (Leak Detection and Repair) are still ongoing, according to the Dutch National Inventory Report (NIR).

Emissions in this segment also display significant differences when comparing the US and Russia, despite a similar developed transmission network. Figures here display an inversion in emission rates: 0.9% for Russia against 0.2% for the US. The distribution sector in the four countries analysed here also displays large variance, ranging from about 0.04% in the Netherlands to almost 0.4% in Germany. The US also presents a leakage rate below 0.1% (Fig. 9). Taking into account the lack of independent research in this sector overseas (especially if compared to the production system), we emphasise the qualitative character of these estimates and the absence of a comprehensive (and highly needed) understanding of the real emissions entity.

Only a few countries have recognised methane as a major climate issue, and therefore developed legislation on methane emissions reduction. The Obama Administration underlined its commitment to slowing climate change and, in this context, reducing methane emissions. Therefore, in January 2015 an INDC was announced – to cut methane emissions from the O&G sector by 40–45% from 2012 levels by 2025. Thus, declared reduction measures include the set of common sense standards for methane, enhancing leak detection, improvement of leak quantification and others.[48] Russia introduced environmental charges as early as the 1990s. The Federal Service for the Supervision of Natural Resources (Rosprirodnadzor)[49] defines maximum permitted concentrations of pollutants, in particular methane. Non-compliance with these regulations can result in minimum (for emissions within the limit values), medium (for emissions within temporary emission limits) or high charges (for emissions that exceed temporary emission limits).[50] For example, the base charge for methane emissions is $0.62/ton of methane; emissions within temporary emission limits = $3.12/ton of methane; emissions above temporary emission limits[51] = $15.62/ton of methane.[52] Joint projects to assess methane leakage from the gas system in Russia have been carried out by Gazprom in cooperation with numerous international partners: the US EPA (1995), Ruhrgas (1997), the Max Planck Institute/the Wuppertal Institute (2002), the Wuppertal Institute/E·ON (2005, 2007), the IEA (2006), the US Pacific Northwest National Laboratory (2010) and Gasunie (2014).

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[48] White House (2015), available at: https://www.whitehouse.gov/the-press-office/2015/01/14/fact-sheet-administration-takes-steps-forward-climate-action-plan-anno-1. Last accessed on 20.12.2016.

[49] Both the Federal Service for the Supervision of Natural Resources (Rosprirodnadzor) and the Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) are services within the Ministry of Natural Resources and Environment.

[50] Evans, M., Roshchanka, V. (2014). Russian policy on methane emissions in the oil and gas sector: A case study in opportunities and challenges in reducing short-lived forcers. – *Atmospheric Environment, 92*, pp. 199–206.

[51] Due to devaluation of the ruble, charges became lower in USD equivalent. For comparison, in 2013 they amounted to $1.57 per ton, $7.85 per ton and $39.25 per ton respectively.

[52] Government of the Russian Federation (2014). *Governmental Decree No. 344*. Available at: http://docs.cntd.ru/document/901865490. Last accessed on 20.12.2016.

4.3 Reasons for emission data discrepancies

There are several reasons for the different methane emission estimates reported so far: Although regional standards and technologies in use can represent the primary source for discrepancies among countries, poor understanding of the real entity of the phenomenon can also play a prominent role.

To explain the offset observed in the distribution sector between Germany and the Netherlands, in a scenario where similar equipment is in place, raises additional questions: pipeline extension per unit of gas distributed per capita in Germany should be higher in order to justify this offset, although this is not the case in reality. This inconsistency is instead better explained by the emission factors reported by the two countries, both based on the Tier 3 approach (country-specific, technology-based emission factors available). The average coefficient accounting for the material mix in the pipeline network is 175 Kg/km for Germany, while for the Netherlands it is not specified but we assume a range of 35–51 Kg/km (the emission factors for low- and medium/high-pressure plastic pipeline respectively). In practice, only 3.5% of the entire Dutch pipeline grid is still made from grey cast iron material (no data are reported for steel and ductile cast iron pipes), supporting the conservative character of the values. Steel, ductile- and grey cast iron pipelines have significantly higher emission factors, ranging from 62 kg/km to 445 kg/km.[53] Nevertheless, the share of grey, ductile and steel cast iron in Germany has also decreased considerably in recent years, accounting for 0.08%, 2.4% and 7.8% respectively.[54] Based on the available data, this large discrepancy between emission factors in the two countries cannot be ascribed to the pipe material.

The adoption of different reporting methods, their quality and the low accuracy of emission factors and activity data are also crucial considerations for these discrepancies, while other elements such as the state of national infrastructure (i.e., pipeline status, materials and maintenance standards) are not always comprehensively accounted and need to be further investigated. Therefore, significant divergences of emissions in the four countries examined here are arguable, considering the similar energy system substrates and technologies in place along the production chain. Furthermore, marked differences in emission factors (e.g., from plastic pipelines), although related to national regulations and measurements, hardly reflect reality. Despite differing regional regulations, contractors and service companies in the upstream sector operate internationally, applying similar field technologies and standards worldwide. As already discussed, numerous measuring campaigns in the US revealed the real climate implications of these activities and provided empirical estimations. A similar situation can be ascribed in Germany, especially for the transmission and distribution sector. The Federal Environmental Agency (UBA) prepares the German NIR for submission to the UNFCCC, and receives data and other information (e.g., emissions factors, results from latest measuring campaigns, etc.) from business associations and institutions such as BVEG (former WEG), DVGW and the German Association of Energy and Water Industries (BDEW).[55] Gas distribution pipelines are subject to regular controls, and emissions factors are constantly improved. Here, calculations have been based on the Tier 3 method, according to data provided by BDEW and UBA, the latter also author of the NIR. Emission factors have been certified by measurements run in the last year and published by DBI, an independent body that conducts measurements and analyses. German emis-

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[53] UNFCCC (2016). *Germany, Common Reporting Format*. Available at: http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php. Last accessed on 20.12.2016.

[54] Deutscher Verein des Gas- und Wasserfachen e.V. (2016). Bestands- und Ereignisdatenerfassung Gas – Ergebnisse aus den Jahren 2011 bis 2014. *Energie, Wasser-praxis*. Available at: http://www.strukturdatenerfassung.de/fileadmin/strukturdaten/gasstatistik2011_2014.pdf. Last accessed on 20.12.2016.

[55] Wirtschaftsverband Erdöl- und Erdgasgewinnung e. V., Deutscher Verein des Gas- und Wasserfaches e. V., and Bundesverband der Energie und Wasserwirtschaft e. V., respectively.

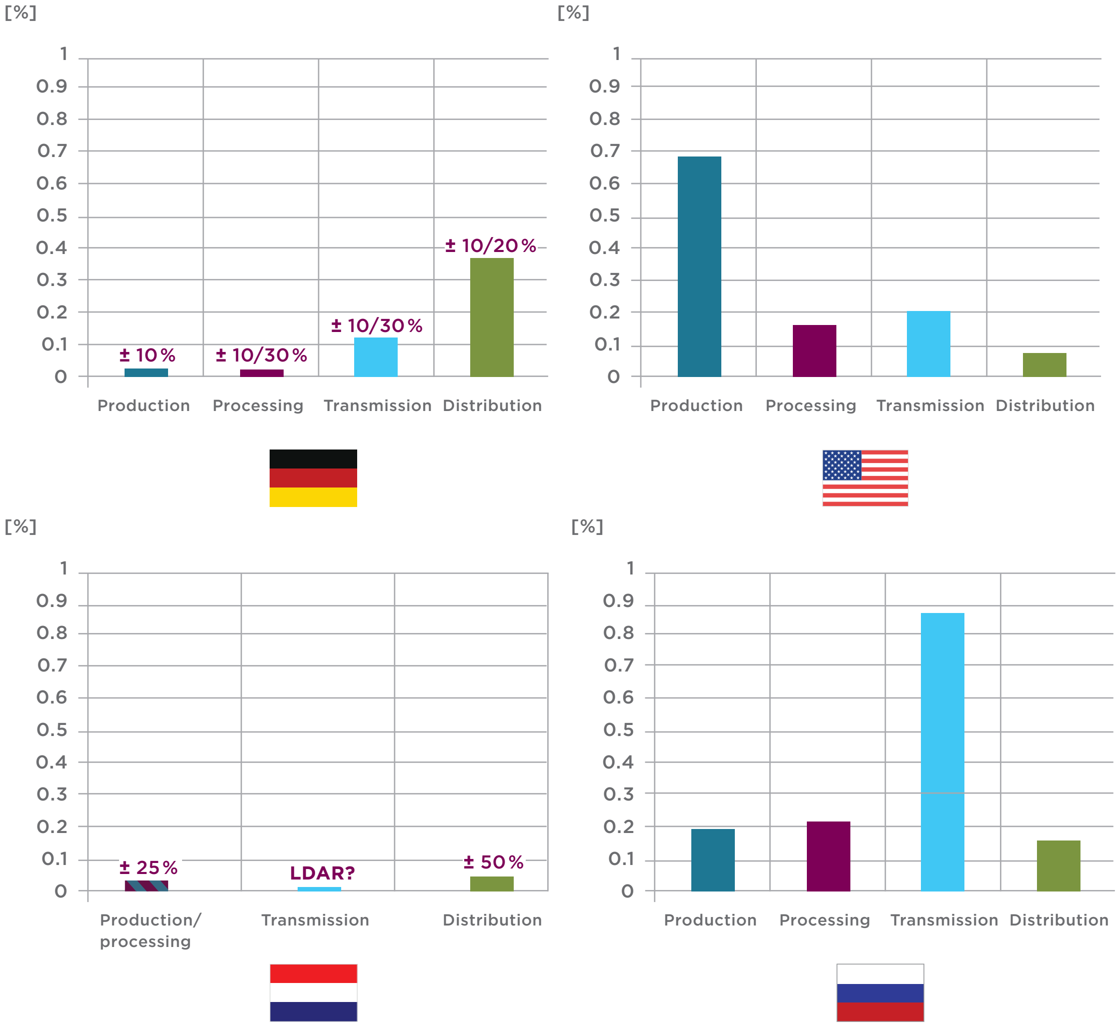

Figure 9: Methane leakage rates from natural gas system in Germany, the Netherlands, Russia and the US (percentage of total gas handled).

Source: Inventory reports to the UNFCCC, 2016, BMWi 2014, NLOG, EIA, BVEG (former WEG). Transmission and distribution sectors values were calculated according to our assumptions and should therefore be considered qualitative in character. The red labels on the histograms represent uncertainty, as reported in the UNFCCC National Inventory Report (NIR); LDR (Leak Detection and Repairs).

sions, from exploration to production, are instead based on estimates made by national experts and business partners that, to our knowledge, are not supported either by publicly available measurements or by external, independent studies. It is therefore difficult to assess how these emissions are estimated and hence to evaluate their accuracy.

As discussed, together with transmission line (the emission factors for which also underwent rigorous certification processes), the distribution (and to a lesser extent transmission) segment has undergone deep investigations in recent years, as has the US production sector. It is perhaps not a coincidence that German distribution pipelines and US production sites are responsible for almost 50% and more than 60% of total emissions respectively – much more than other segments and/or countries. Targeted surveys seem to translate to upward revision of methane emission inventories, an aspect that should warn of the general unreliability of outdated databases and under-investigated sectors.

Figure 10: Main causes of data discrepancies.

- Different emission calculation methodologies and/or devices used while measuring;
- Different measuring years (with implications on technologies) and lack of updates;
- Country-specific requirement/control on data quality and national measuring surveys;
- Different reporting systems for the UNFCCC reports (i.e., Tiers);
- Different levels of investigation in the sub-sectors (production, etc.);
- Different emission factors for similar infrastructure (e.g., pipelines);
- Activity data are often incomplete;
- Specific pipeline structure and population density;
- Quality of national infrastructure.

Another hurdle when comparing different countries is the differing methodologies used to calculate emissions. As previously mentioned, there are three methods recommended for reporting emissions for compliance with the UNFCCC standards, each of which is to be adopted according to national database quality, which also pertains to different levels of complexity. The simplified approaches (called Tier 1) with default emission factors from the IPCC guidelines have high uncertainty and often result in higher emission estimates in comparison to other methodologies. More sophisticated approaches (called Tier 2 and Tier 3), with country-specific emission factors to capture different elements of the gas grid, are more reliable and accurate.[56] Nevertheless, these specific emission factors are also often the result of different emission investigation techniques established in foreign countries (as reported in Fig. 10). These marked operational differences, sometimes recorded even within the same country, inhibit consistent and comparable emission estimates in the gas sector across Europe. Initiatives in cooperation with international partners are assessing the real extent of comparisons, and seek to pinpoint possible unified methodologies to be deployed in European countries.[57]

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[56] For more information, please refer to: IPCC (2006). *Task Force on National Greenhouse Gas Inventories*. Available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/. Last accessed on 20.12.2016.

[57] See for example: http://www.gerg.eu/. Last accessed on 20.12.2016.

- Method of Battelle 1989 → applied by Belgium, (Italy)
- Method of Battelle 1994 → applied by Switzerland
- Method of FH ISI 2000 → applied by Germany, Netherlands (Sweden)
- Method of Stoller-DBI 2012 → applied by Germany
- Method of British Gas/National Grid → applied by United Kingdom
- Method of GRDF/ENGIE → applied by France
- Method of Gas Natural Fenosa → applied by Spain
- Method of EPA → applied by USA
- Method of IGU 2000/IPCC Guidelines 2006 → applied by Romania
- Method per Sale of Natural Gas → applied by Poland
- Method of Marcogaz 2005 → estimation at EU level

Figure 11: List of methods[58] for estimating emissions in the gas distribution grid examined in the GERG-project.

Source: DBI GUT GmbH.

Another example of data discrepancy arising from the use of different methodologies is evident in the case of Russia. Even among national inventories, the variance is remarkable: Figure 12 shows emissions assessments reported by Gazprom and the Federal Institute for Global Climate and Ecology, which prepares and submits Russia's reports to the UNFCCC. In its assessment, Gazprom applies a nationally certified methodology that, however, has not been yet "officialized" under the IPCC standards. Thus, default emission factors for developing countries are used when calculating Russian emissions.[59] However, submission of a national emission methodology for IPCC approval is planned, and might considerably decrease the extent of emissions.

[58] Italy applies emission factors from Battelle but also from other sources. According to the Swedish National Inventory Report (NIR) 2014, Sweden applies an emission factor that was developed for the Dutch distribution grid, using the method from FH ISI. GRDF/ENGIE is the ENGIE Group research and operational expertise centre, dedicated to gas, new energy sources and emerging technologies. GNF applies emission factors provided by Marcogaz and other studies. The only exception is for polyethylene medium-pressure networks, where emissions are estimated using EFs determined by own measurements with pressure variation method (PVM).

[59] Davydova, A. (2016). Gazprom and Roshydromet disagreed on the estimates of methane emissions in Russia. – Kommersant, in Russian. Available at: http://www.kommersant.ru/doc/2984626. Last accessed on 20.12.2016.

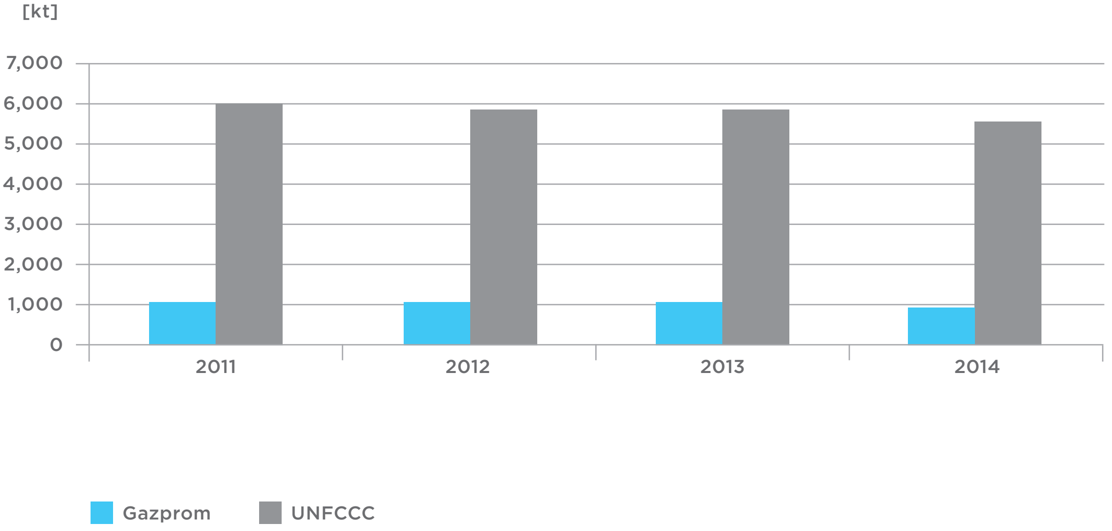

Figure 12: Methane emissions from natural gas system in Russia (kt of CH_4).

Source: Gazprom environmental reports, Russian inventory report submitted to the UNFCCC, 2016.

The large majority of analysed publications on methane emissions worldwide demonstrate that very few emission factors have been verified by empirical measurements. An investigation conducted by the Oil and Gas Institute in Poland,[60] which calculated emission levels for a virtual gas system using different methodologies, shows a substantial discrepancy between results, ranging from 30 to 170 Gg (specifically: 13–55% in transmission, and 42–85% in the distribution segment). Accordingly, the study states that *"emission factors inventory relying exclusively on literature values produce results with extremely high uncertainty"* and concludes that *"own measurements are always indispensable, at least in order to confirm the emission factor choice."*

4.4 Emissions in conventional and unconventional natural gas

In the context of analysing methane emissions during gas recovery, it is important to discuss different exploitation techniques employed in the countries here investigated since these might be partially responsible for the large variance in methane emissions shown in this report. While hydraulic fracturing is widely performed in shale reservoirs in the US, this technique is only used in specific European basins. Classification of natural gas as conventional or unconventional is somewhat arbitrary and not strictly linked to geological parameters of the reservoir nor of the gas, thereby resulting in some confusion, especially among non-experts. For example, tight gas (i.e., gas stored in reservoirs with low permeability that therefore needs to be fractured) is categorised within the *unconventional* resources group in the US,[61] while in Europe it is generally classified as a *conventional resource*.[62] Especially in the US, the term 'tight' is sometimes used to refer to any gas reservoir with reduced permeability that therefore requires hydraulic fracturing, in order to differentiate them from the conventional gas basins.

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[60] Oil and Gas Institute (2003). *Inventory of Methane Emissions from Gas Industry – The Problem Solved or Still Opened?* Available at: http://members.igu.org/html/wgc2003/WGC_pdffiles/10292_1045234635_15234_1.pdf. Last accessed on 20.12.2016.

[61] Total, available at: http://www.total.com/en/energies-expertise/oil-gas/exploration-production/strategic-sectors/unconventional-gas/presentation/three-main-sources-unconventional-gas. Last accessed on 20.12.2016.

[62] Wintershall, available at: http://www.wintershall.com/en/different-types-of-reserves-tight-gas-and-shale-gas.html. Last accessed on 20.12.2016.

Measurement campaigns on O&G producing sites in the US are key for defining strategies against gas losses. Suspect high methane concentrations have been detected above almost all the gas plays as well as in regions where oil is produced, regardless if from unconventional reservoirs. Emissions of methane, other volatile organic compounds and oxides of nitrogen can occur during all stages of gas exploitation of both conventional and unconventional reservoirs. Specifically, it has been demonstrated that differences in life cycle assessments (LCAs) between conventional and shale gas are negligible if best practices are adopted.[63] While considering fugitive emissions and venting, the principal disadvantage of shale gas against conventional gas is in the larger volume of liquids that is recollected at the drilling site that needs to be treated. Production of gas or oil without hydraulic fracturing also entails separation of liquids due to the usual presence of saline water in the reservoir (i.e., formation or geogenic waters).[64] According to Khatib and Verbeek (2003),[65] the amount of produced water generated by the O&G institute amounted to almost 300 million m^3 back in 1999, prior to the invention of High Volume Hydraulic Fracturing (HVHF) to exploit shales. Because of the larger volume of liquids collected and handled per unit of gas (or oil) produced during shale exploitation, there is a greater risk of substantial release of gas to the atmosphere. Of the total volume of fracking waters injected underground, between 20% and 300% are recollected at the well site[66] together with a variable portion of saline waters originally present in the reservoir, before (flowback waters) and during production (produced waters). The volume of liquids requiring treatment is therefore not strictly determined by the original volume of water injected. For example, in the Eagle Ford and Marcellus shales, the volumes of produced waters per well are generally small, while in the Barnett play the mean ratio of produced waters to fracking waters exceeds 100% after one year, and reaches 200% in six years.[67] Separation of liquid and gas (i.e., well completion) is conducted inside special sealed chambers and can contribute greatly to increase total gas fluxes to the atmosphere if green completion (also called Reduced Emissions Completions, RECs) is not implemented.[68] Differently, if this operation is properly conducted as described by the EPA,[69] the potential loss of gas can be considerably reduced if not eliminated.[70] It has been estimated that, through the implementation of RECs that became mandatory for operators active in

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[63] Burnham, A., Han, J., Clark, C. E., Wang, M., Dunn, J. B. Palou-Rivera, I. (2012). Life-cycle greenhouse gas emissions of shale gas, natural gas, coal and petroleum. – *Environmental Science & Technology, 46*, pp. 619–627; Department of Energy and Climate Change, DECC (2013). *Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use*. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/237330/MacKay_Stone_shale_study_report_09092013.pdf. Last accessed on 20.12.2016; Westaway, R., Younger, P. L., Cornelius, C. (2015). Comment on 'Life cycle environmental impacts of UK shale gas' by L. Stamford and A. Azapagic. – *Applied Energy, 148*, pp. 489–495; Weber, C. L., Clavin, C. (2012). Life cycle carbon footprint of shale gas: review of evidence and implications. – *Environmental Science and Technology, 46*, pp. 5688–5695.

[64] Argonne National Laboratories (2004). *A White Paper Describing Water from Production of Crude Oil, Natural Gas and Coal Bed Methane.* Available at: http://www.ipd.anl.gov/anlpubs/2004/02/49109.pdf. Last accessed on 20.12.2016.

[65] Khatib, Z., Verbeek, P. (2003). Water to value—produced water management for sustainable field development of mature and green fields. – *Society of Petroleum Engineers*, 55, pp. 26–28. SPE-73853-PA.

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the US since January 2015, between 90% and 95% of vented gas can be captured.[71] Further processes that the gas will undergo after its separation from the liquid mixture are independent of the exploiting practice. All steps such as separation of oil and gas, water, condensates, hydrogen sulfide, CO_2 and Natural Gas Liquids (NGLs); as well as the introduction into the pipeline network to reach the location of final use, can all potentially be sources of leaks for any form of gas. Among the most common, well workovers consist of invasive interventions on gas or oil wells, including re-fracturing operations that are occasionally necessary to sustain shale gas well production. During this practice, if RECs measures are correctly implemented during the collection of flowback waters, the amount of gas emitted can be substantially reduced for both conventional and unconventional wells. Similarly, liquid unloading is a practice used to remove water and liquids that clog mature wellbores, aimed at restoring the normal gas flow. If specific measures are not employed to minimise gas losses (i.e., plungers lifts, positive displacement systems and others), this practice can imply large gas emissions.[72] Although some authors tended to associate liquid unloadings with shale gas wells only,[73] recent evidence suggests that this is a common practice for all onshore conventional gas and shale.[74] The volumes of geogenic and flowback waters that are sequestrated from the reservoir can differ between basins and affect the frequency of such operations to a greater extent than the nature of the gas.

Generally, lower Ultimate Recovery Rates (URR) of shale gas wells are mostly responsible for the higher gas losses reported in different studies.[75] Accordingly, punctual emissions such as re-fracturing and flowback water treatments are generally assigned higher proportional contributions when calculating emission.[76] If these exceptions are tackled by means of engineering practices, there is no scientific evidence, to date, that the issue of gas losses relates exclusively or largely to shale gas basins, but it can permeate the entire gas recovery sector.

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5. Conclusions

High levels of methane emissions have tremendous negative impacts on climate, and are of particular concern if considering the anticipated increases in global O&G production. On one hand, curbing methane emissions provides a tangible opportunity to achieve rapid progress toward slowing climate change and improving air quality; on the other, the lack of effort to resolve this issue undermines the green credentials and potential for natural gas to act as a bridging fuel to future renewable energy generation. The acknowledged importance of curbing methane to tackle climate change, and the high contribution from the fossil fuel sector, both call for rapid and collaborative endeavours to systematically address the unknowns that persist in this field.

Inconsistencies in methane emission estimates in different regions cannot always be explained simply by regional settings, especially considering countries that have comparable regulations regarding infrastructures and environmental standards. Moreover, the continued underestimation of the importance of emissions makes it difficult to assess the real status of methane leaks from the European and German natural gas systems. In our view, this is mostly due to large uncertainties resulting from inconsistent methodologies; poor reporting and measurements; and the knowledge gaps that still exist regarding methane emissions during gas production.

The paucity of data on methane emissions from gas systems worldwide leads to an ambiguous climate footprint of the different natural gas sources in Europe, supplying Europe (Netherlands, Russia, Norway, US and Qatar) and beyond. Among the relevant questions, the following are most urgent: What are the best methane emission abatement strategies? Which policies and regulatory regimes are necessary to achieve significant effects in the short term? The sources of methane emissions and technologies to reduce them are well-known and cost-effective.[77] Furthermore, numerous measurements undertaken in the US and Russia show that the largest part of these emissions originate from a small number of sites (so-called super-emitters) that could be cost-effectively targeted.[78]

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Encouragingly, we observe increasing interest in the topic of methane emissions by governments, EU institutions and the general public. Presently, a number of projects on methane emissions reduction are underway, led by the UN, the IEA, the European Commission and other organisations. To deliver tangible results, cooperation between research institutes, policy makers and the business community is indispensable. A joint international effort to address the various issues associated with methane leakage estimation and IPCC guidelines would not only provide invaluable insight for participating scientific, governmental, and private sector actors, but would also elevate the saliency of this issue for global climate change mitigation efforts. More specifically, a joint effort involving key national governments within Europe and internationally (such as the EU, Germany, Russia and the US) could put the issue of methane leaks from the O&G industry on the political agenda at the next critical inter-state meetings such as the G20 and COP23.

Despite some progress, large knowledge gaps and uncertainties remain. A small fraction of methane leakage will have severe consequences for our climate, particularly in view of crossing tipping points in the climate system, which would lead to unpredictable and potentially disastrous global consequences. From a sustainability perspective, we need therefore to emphasise the urgency for actors in climate and energy policy as well as the gas industry in particular, to quickly shed light on these delicate blind spots and the real impacts of natural gas. Given the indicated differences and potential flaws in today measurements, these assessments need to be both based on scientifically sound methods and comply with high standards of transparency for both measurements and data. Our precautionary principles imply that, unless quickly and definitively proved otherwise, we need to consider high methane losses a realistic conclusion, based on which natural gas cannot be recommended as feedstock of sustainable energy systems nor as a bridging fuel for the transition towards a renewables-based energy system. ■

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