

RESEARCH ARTICLE

Emission scenarios of a potential shale gas industry in Germany and the United Kingdom

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The shale gas debate has taken center stage over the past decade in many European countries due to its purported climate advantages over coal and the implications for domestic energy security. Nevertheless, shale gas production generates greenhouse gas and air pollutant emissions including carbon dioxide, methane, carbon monoxide, nitrogen oxides, particulate matter and volatile organic compounds. In this study we develop three shale gas drilling projections in Germany and the United Kingdom based on estimated reservoir productivities and local capacity. For each projection, we define a set of emission scenarios in which gas losses are assigned to each stage of upstream gas production to quantify total emissions. The “realistic” (REm) and “optimistic” (OEm) scenarios investigated in this study describe, respectively, the potential emission range generated by business-as-usual activities, and the lowest emissions technically possible according to our settings. The latter scenario is based on the application of specific technologies and full compliance with a stringent regulatory framework described herein. Based on the median drilling projection, total annual methane emissions range between 150–294 Kt in REm and 28–42 Kt in OEm, while carbon dioxide emissions span from 5.55–7.21 Mt in REm to 3.11–3.96 Mt in OEm. Taking all drilling projections into consideration, methane leakage rates in REm range between 0.45 and 1.36% in Germany, and between 0.35 and 0.71% in the United Kingdom. The leakage rates are discussed in both the European (conventional gas) and international (shale gas) contexts. Further, the emission intensity of a potential European shale gas industry is estimated and compared to national inventories. Results from our science-based prospective scenarios can facilitate an informed discussion among the public and policy makers on the climate impact of a potential shale gas development in Europe, and on the appropriate role of natural gas in the worldwide energy transition.

Keywords: Shale gas; Unconventional gas; Methane leakage; O&G industry; Fracking; Natural gas

Introduction

Over the past decade there has been a rapid increase in natural gas production in the United States (US), mainly due to shale gas, which accounts for about 60% of current total production (WEO, 2017). As the name suggests, shale gas is natural gas that comes from shale reservoirs. Shale, a fine-grained, laminated, sedimentary rock, has an extremely low permeability which in the past made extraction of this gas type difficult and hence uneconomical. However, advancements in horizontal drilling and hydraulic fracturing in recent years have unleashed previously unrecoverable shale gas reserves to large-scale, commercial production (Jenkins and Boyer, 2008; Gregory et al., 2011).

Natural gas is often described as a transition fuel on the road to a decarbonized global energy system. This is because natural gas generates less carbon dioxide (CO_2) emissions during combustion per unit of energy than coal or oil (WEO, 2017), and therefore enables continued fossil fuel use with an ostensibly smaller impact on the climate. However, methane (CH_4) – the main component of natural gas – is a powerful greenhouse gas (GHG). On a mass-to-mass basis, CH_4 warms the planet 87 times that of CO_2 over a 20-year timescale, and is 36 times more warming over a 100-year timescale (IPCC, 2014). Indeed CH_4 emissions (here also reported as losses) are generated during the various stages of natural gas production. In this study we distinguish emissions of CH_4 as follows: fugitive emissions (as a result of accidental leaks; e.g., damaged gaskets or pipes, incidents, etc.); gas venting (intentional design of machinery such as pneumatic device venting, equipment blowdowns, etc.), and associated emissions, such as CH_4 emitted by associated activities (e.g., trucks, indirect emissions induced by electricity usage, etc.).

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CH_4 emissions additionally have a negative effect on public health due to the role of CH_4 as a precursor of ground-level ozone (O_3 ; Garcia et al., 2005). Furthermore, natural gas extraction and processing leads to emissions of air pollutants including volatile organic compounds (VOCs), nitrous oxides (NO_x), carbon monoxide (CO), and particulate matter (PM), which negatively affect human and environmental health (Dockery and Pope, 1994; Kampa and Castanas, 2008; Roy et al., 2014; Sweileh et al., 2018). The dramatic increase in shale gas exploitation has therefore raised concerns about the burden on the climate and air quality. Accordingly, many studies have been conducted over the past years to examine the influence of shale (also called unconventional) and conventional gas production on emissions, and on CH_4 emissions in particular. Especially in Europe, it is a shared belief among societal and political actors that emissions from conventional gas production are substantially lower than those from shale gas (DW, 2018; Energate, 2018; Zittel, 2015; Greenpeace, 2015; Howarth, 2014). Although this was probably the case at the onset of the shale gas boom when fracking operations were not properly regulated (e.g., open pits for storing flowback waters, improper well completion, etc.), rigid environmental standards are largely in place to date in the US. The latest scientific literature on this topic is still ambivalent, and the preliminary – despite insufficient – data available seems to not support this large discrepancy: as reported in Zavala-Araiza et al. (2015), about 50% of emissions investigated in their study are attributed to compressor stations and processing plants, and therefore sources unrelated to the production technique. The remaining share is generated at production sites extracting both conventional and shale gas. Therefore, in the extreme and unrealistic case where hydraulic fracturing (i.e., the recovery technique employed during shale gas extraction) were the only CH_4 source at production sites, the unconventional gas production chain would generate about three-fourths of total emissions associated with natural gas production in the US.

In support of this, hydraulic fracturing appears to not be responsible for larger emissions according to results by Allen et al. (2013), despite the fact that emission budgets here might be underestimated due to the bottom-up data method applied (Brandt et al., 2014). Although Reduced Emissions Completions (RECs) – a practice needed only at shale gas wells and able to cut emission by at least 90% during well completion (EPA, 2014a) – have been mandatory in the US since January 2015, studies still continue to measure very high losses from overall gas recovery activities. One explanation might be that gas released during well completions, often alleged to be responsible for augmented emissions at shale gas wells, have only a minor contribution to total budgets. For example, Alvarez et al. (2018) estimate an upstream leakage rate of 1.95% from about 30% of all existing oil and gas wells in the US without reporting any evident discrepancy between these two natural gas categories both present among the gas plays analyzed. Yet, the EDF chief scientist and co-author of the study stated that “most [of the emissions detected] are tied to hatches and vents in natural gas storage tanks

at extraction wells”,¹ sources that can occur at any stage along the production chain and are therefore not necessarily linked to fracking operations. Results from Omara et al. (2016) show a correlation between the CH_4 leakage rate and age of the wells rather than the nature of the gas, proving that impacts related to other factors may, at least occasionally, be greater than gas type. Data available for European gas plays is yet scarce. While US shale gas leakages reported in Howarth (2014) can be higher than 10%, data for conventional gas in countries like Germany and the UK (NIR 2017) shows instead leakage rate below 0.1%. This large emission discrepancy is widely applied to narratives on natural gas usage in the European context to oppose unconventional gas development. Nevertheless, Yacovitch et al. (2018) found high uncertainty in emission inventories from oil and gas wells in the Groningen Field in the Netherlands, and the occurrence of an unidentified offshore super-emitter source. Moreover, preliminary quantification of CH_4 losses at North Sea offshore oil and gas platforms suggest much higher estimates than those reported by the UK national emission inventory, up to 0.70% of the total gas produced (Riddick et al., 2019). All of these studies performed in the US and emission discrepancies with European datasets do not conclusively prove large offsets between emissions from shale gas and conventional gas activities, and specifically do not explain much more conservative emissions for the latter. At the same time, they neither prove the opposite. The emission contribution of shale gas and conventional gas to total gas losses remains unclear to date, and further research is needed to reconcile emission budgets and rates among these regions. This argument is further examined in the “Results and discussion” Section.

Notwithstanding that shale gas production has occurred primarily in the US, global shale gas resources are considerable, amounting to >200 tcm (trillion cubic meters) – or rather, about one third of the world total technically recoverable natural gas reserves (EIA, 2013). Several European countries, including Germany and the United Kingdom (UK), have expressed interest in recent years in utilizing domestic shale gas assets as part of their national energy agenda. Although shale gas reserves in Germany and the UK are substantially smaller than those found in, e.g., the US, production of shale gas has the potential to offset or slow down the decline in conventional gas production that these countries are experiencing. This would avoid increased dependency on foreign gas imports, as well as avoid a potential increase in coal use for electricity generation. However, opposition from the general public and environmental interest groups on account of potentially harmful effects from shale gas fracking activities – for example, surface and groundwater contamination (Osborn et al., 2011; Jackson et al., 2013; Darrah et al., 2014; Drollette et al., 2015), increased frequency of earthquakes (Ellsworth, 2013), as well as increased emissions as discussed above (Oltmans et al., 2014; Swarthout et al., 2015; Hildenbrand et al., 2016) – has led to moratoria and bans in various regions and countries like in France and Germany. In the latter, the government recently placed a ban on unconventional fracking at least until 2021 (Bundesregierung, 2017).

In the context of sustainability, a responsible energy strategy with regard to shale gas production in Europe requires sound scientific advice. Studies that explore what the range of impacts that a potential European shale gas industry would entail, as well as opportunities to reduce potentially harmful effects, are still missing although necessary to inform policy. Here we examine the impact of a potential shale gas industry in Germany and the UK – two countries where political and social discussion on shale gas has been intense over the last years – on GHG and pollutant emissions, including CH_4 , CO_2 , VOCs, NO_x , CO, PM_{10} and $\text{PM}_{2.5}$ ($\text{PM} \leq 10 \mu\text{m}$ and $\leq 2.5 \mu\text{m}$ in diameter, respectively) through emission scenarios. First, we give an overview of shale characteristics and examine the shale reservoirs considered in this work. Then, we discuss how the drilling projections and emission scenarios are developed for Germany and the UK. Next, we describe each of the scenarios that we designed, including the data that we incorporated and assumptions that we made. Subsequently we present the results, i.e., the impact of shale gas operations on emissions per each scenario. Finally, we analyze the impact on these two countries, putting the emissions into context with current inventories to develop and transfer findings to policy-makers. The aim of our scenarios is to understand what a shale gas industry in Europe may look like, to show how regulation and compliance (along with uncertainty ranges) may impact emissions, and to present opportunities for air quality and emission mitigation.

Other potential consequences of shale gas production, such as surface and water contamination, seismic activity, and an offsetting of emissions from coal in electricity generation due to availability of natural gas, are important but outside the scope of this study and are not be considered here. A follow-up study will explore the potential impact of shale gas emissions on local and regional air quality in Europe through atmospheric chemistry modelling.

Methodology

In this study we investigate realistic shale gas industrial developments in Germany and the UK, and quantify their associated GHG and air pollutant emissions. In order to do this, we first develop drilling projections in which we estimate the total number of “wells under construction” and “producing wells” required to achieve and maintain steady-state gas production in the two countries of reference, based on varying degrees of well productivity. After that, we quantify emissions associated with upstream production through a bottom-up approach in different scenarios covering a series of well productivity and technology/performance cases. The results presented here are plausible under specific geological and technological/performance conditions selected in this study and consistent with the existing scientific literature. Results and their interpretation reported in the discussion section, as well as their scientific relevance, have to be therefore evaluated taking such constraints into account. Additionally, a sensitivity analysis of the emission scenarios is performed and is provided in the SM, Text S1, Section S3. The purpose of this is to examine the contribution and influence of each varying

parameter on the final results to guide the selection process of such parameters.

Shale characteristics and gas extraction

Shale is a sedimentary type of rock that is generated by the compaction of deposits containing silt- and clay-size particles. While shale is characterized by extremely low permeability, it possesses a high porosity. It is in these pores that the organic material and gas molecules are located, as free gas or adsorbed on organic remains (Glorioso and Rattia, 2012). During the shale gas extraction process, a vertical shaft is initially drilled. Then, when the vertical drill path reaches the target shale formation – usually between 1,000 and 4,000 m underground depending on local geological features – its direction is shifted horizontally to follow the shale plane (Elsner and Hoelzer, 2016). Afterwards, water, sand, and chemicals are injected at high pressure to create fractures in the rock during the hydraulic fracturing or “fracking” process, increasing permeability of the formation and thereby stimulating gas flow to the well (Gregory et al., 2011). Although most public attention tends to focus on the hydraulic fracturing, this recovery technique was performed experimentally in 1947 and has actually been in widespread use in Germany since the 1960s (LBEG, 2010; Wilson and Schwank, 2013). In fact, horizontal drilling is the more recent technology and game changer that has made commercial shale gas production possible. Horizontal wells – which can extend over several kilometers – maximize contact with the shale payzone which is typically spread out in narrow, horizontal bands, whereas vertical wells can only provide a small, insufficient portion of contact (Pearson et al., 2012; ACATEC, 2016). Furthermore, directional drilling is used to reach targets beneath adjacent lands, intersect fractures, and drill multiple wells from the same vertical borehole (Elsner and Hoelzer, 2016), thereby maximizing the shale gas yield while reducing the surface environmental footprint.

Shale reservoirs considered in this study

The shale gas reservoirs taken into account in the present study are based on recent studies which aimed to quantify the relevance of shale gas as a national energy asset by both the German and British governments. In its 2016 report, the Federal Institute for Geosciences and Natural Resources (BGR, 2016) found five shale basins in Germany to be promising for natural gas production: the *Fischschiefer*, *Wealden*, *Posidonien*, *Mitterrät*, and *Unterkarbon* units. These basins are scattered across several federal states, covering a total area of more than 8,000 km², and are buried between 500 and 5,000 m underground. The technically Recoverable Resource (TRR) for these reservoirs ranges between 650 and 1,380 bcm (billion cubic meters), averaging at 940 bcm. By comparison, the UK's geological landscape is characterized primarily by one major shale basin, the Bowland-Hodder Carboniferous Unit. This basin spans an area of 14,000 km² underneath the regions of Yorkshire, North West, East and West Midlands and reaches a maximum depth of 4,750 m below ground. According to the British Geological Survey's (BGS) 2013

report, the total gas-in-place (GIP) buried in this formation is estimated at 37.6 tcm (trillion cubic meter), while the TRR is still unknown. Pilot exploration projects by Cuadrilla are planned and started again in late 2018, after a long break following the Blackpool Earthquake in 2011. The shale reservoir locations in Germany and the UK are shown in **Figure 1**. These basins are selected as the gas reservoirs to be exploited in our drilling projections.

Drilling projections

Three different projections of shale gas well populations are developed for Germany and the UK in this work, referred to henceforth as drilling projections. The drilling projections ultimately provide information on the number of *wells under construction* and *producing wells*, information that is necessary to quantify emissions from shale gas production in the emission scenarios. In the next paragraphs we describe the four main steps involved in building the drilling projections and the critical assumptions made.

Step 1: Basin productivity. We first define the extension of the shale gas prospective basins described in the previous section. Subsequently we considered the Technical Recoverable Resources (TRR), defined by national authorities as the volume of gas that can be produced with currently available technology and practices. The estimated TRR of the shale gas basins is typically provided in an

uncertainty range described by three cases of productivity: 25th, 50th, and 75th percentile of exceedance, which we refer to as P25, P50 and P75. Following the approach adopted by the BGR, the TRR of the Bowland Basin was calculated as 10% of the total GIP range estimated by the BGS. In this study, P25 and P75 signify low- and high-basin productivities respectively, while P50 describes the “most likely” case. Due to the lack of data and to reduce complexity, we assume that each of the six basins contains a homogeneous gas density across their geographical extension (i.e., no hot spots are considered). The gas “density” is calculated for each basin and productivity case. Data are reported in SM Text S1, Table S1. TRR results are showed in **Table 1**.

Step 2: Well Estimated Ultimate Recovery (EUR_{well}). In order to assess the productivity of the wells (the total gas output from a single well during its lifetime) for each productivity case (P25, P50 and P75) and for each basin, we have to define the portion of reservoir that is exploited by a single horizontal well. To do this, we assume that each well pad exploited an area of 25 km², from which 30 horizontal wells are drilled (**Figure 2**; Pearson et al., 2012; Acatech, 2016). Based on the gas densities estimated in step 1, we are able to define the EUR_{well} that characterizes each population of wells. More information on the assumptions on which we base this well geometry is available in the SM, Text S1, Section S1.1.

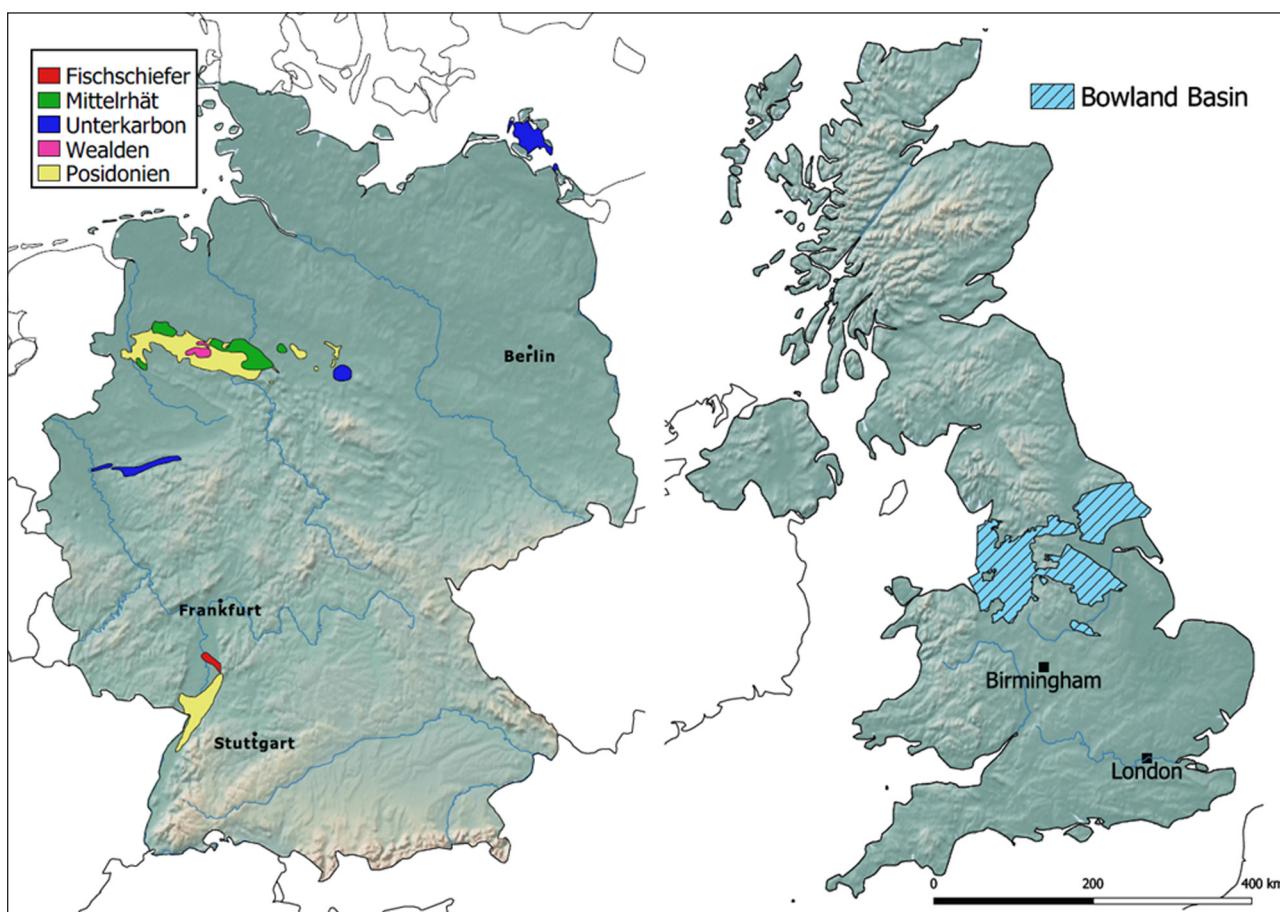


Figure 1: Shale gas basin areas for Germany (left) and the UK (right). Figures include legends with the basin names and their designated color on the map. DOI: <https://doi.org/10.1525/elementa.359.f1>

Table 1: Shale gas basin characteristics and well data at steady-state production. Area and TRR of all shale gas basins for both Germany and the UK. The number of years required to achieve the desired volume of gas for each productivity case under each basin productivity and emission scenario is also indicated. The ranges of *wells under construction* and *producing wells* represent the variance between the upper and lower boundary for each case. DOI: <https://doi.org/10.1525/elementa.359.t1>

Country	Productivity Case	Area [Km ²]	TRR [bcm]	Years to maturity	Wells at the steady-state production				
					Optimistic Emissions (OEm)		Realistic Emissions (REm)		
					<i>Under construction</i>	<i>Producing</i>	<i>Under construction</i>	<i>Producing</i>	
Germany	P25	550	8	162	1,927–1,937	164–166	1,952–1,979	879–891	
	P50		8,341		143	867–872			
	P75				97–98	522–525			
UK	P25	2,866	3	201–202	1,407–1,414	204–206	1,426–1,445	867–879	
	P50		13,736		160–161	856–860			
	P75				110	479–482			

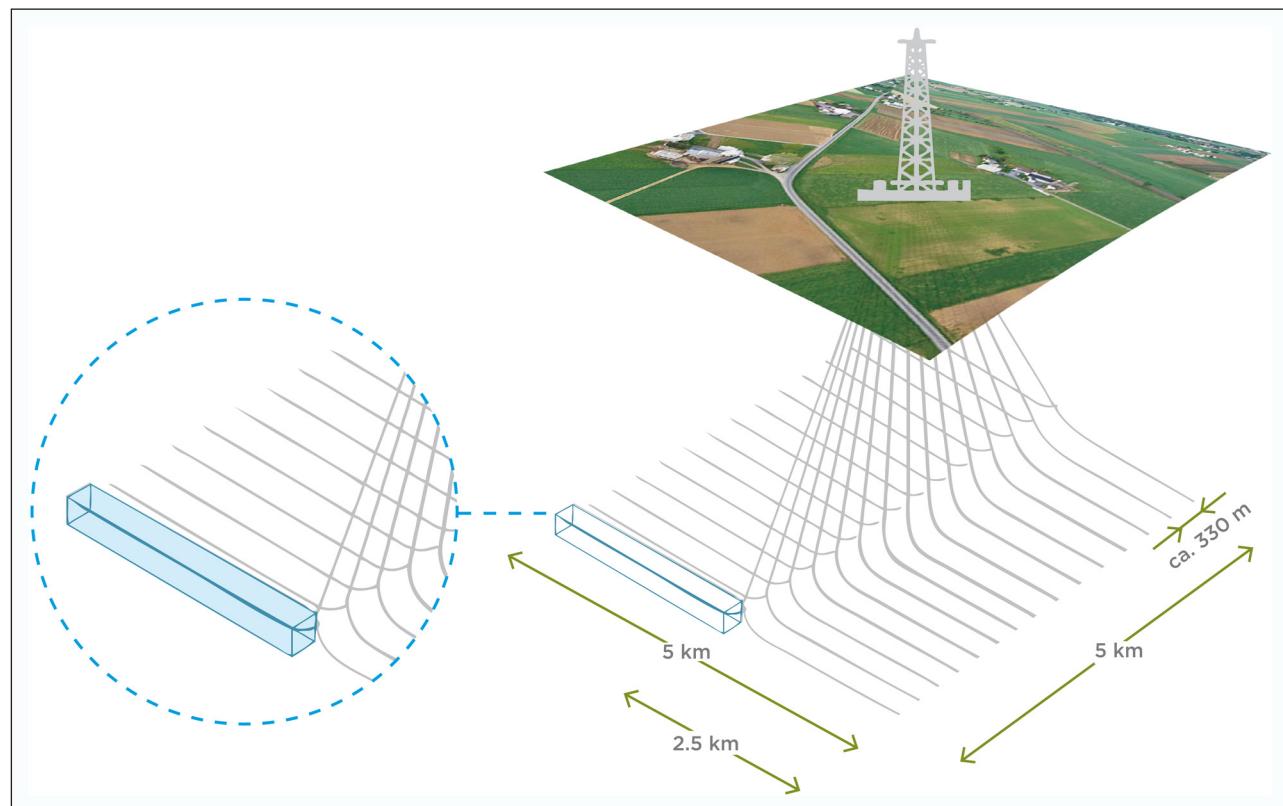


Figure 2: 3D underground view of well geometry. We assume that a total of thirty underground horizontal wells are drilled on a single well pad, which covers an area of 25 km², as shown in the figure. DOI: <https://doi.org/10.1525/elementa.359.f2>

Step 3: Well productivity curve. Shale gas wells present a steep production curve: After about one or two years of sustained production, their yield decreases substantially according to the geological characteristics of the shale reservoir (Patzek et al., 2013). This pattern is generally described by a curve declining asymptotically toward zero production (i.e., exhausted well). Here, we describe how the declining curve of the wells is determined. Once the

EUR_{well} for each basin is defined, we estimate the Initial Production (IP_{well}) of each population of wells through the R_{ie} factor. This coefficient is based on the correlation between EUR_{well} and IP_{well} observed in the Barnett and the Eagle Ford plays, two US basins that show petrological similarities with the German Unterkarbon and the Posidonia shales (BGR, 2016). To reduce complexity, their IPs and production declining rates are averaged and

applied to all the German and UK basins investigated here. R_{ie} is defined as:

$$R_{ie} = \frac{IP_{well}}{EUR_{well}}$$

The resulting production decline curve is best described with an exponential trend in the first year (Patzek et al., 2013), and logarithmic trend for the following four years as shown in **Figure 3**.

For each basin, the same declining pattern describes the production variation over time, specific to each productivity case. After the fifth year, we assume that gas production remains constant because of our limited knowledge of long-term trends.

Step 4: Estimating the population of wells under construction and producing wells. These values are based on regional settings and comparisons with the development rates of US shale plays (Hughes, 2013). We estimated that 200 new wells are drilled each year in Germany and 280 in the UK. These estimates represent the final number of wells drilled, taking into account a failure rate of 20% (i.e., unsuccessful wells). Moreover, the wells are numerically distributed among the different German basins proportionally to the basins' extension. The drilling rates are kept constant in the two countries until a gas output of 11.58 bcm for the former and 36.62 bcm for the latter is achieved at industrial maturity. These two values are selected from among all the gas output results obtained by the three drilling projections developed for each country, since they best fit with historical data and realistic national goals of the region under observation (see discussion in SM Text S1, sections S1). Specifically, they are

selected from the projections Germany P50 and UK P50. Once the gas flowing from *producing wells* – the population of which grows annually due to continuous drilling activity – reaches these volumes, we calculate the number of annual new wells required to maintain this production level for both Germany and the UK. In fact, this parameter varies over time since it depends on the number of existing *producing wells*, their age and declining rate, and the total gas output. Therefore, we considered the average over the following three years. This value, specific to each country and productivity case, is defined as *wells under construction*. The drilling projections also provide details of the number of active wells (i.e., *producing wells*) at steady state production in each country and productivity case. The output data from each drilling projection, namely *wells under construction* and *producing wells*, are used as input in the emission scenarios. The results are shown in **Table 1** and SM Text 1, Figure S1.

Emission scenarios

The emission scenarios are generated by compiling and aggregating emissions estimated at each stage of the supply chain (i.e., from well preparation to gas processing) at industrial maturity. By feeding the system with the outputs parameters of the drilling projections (*wells under construction* and *producing wells*) for both Germany and the UK, we quantify emissions for each country under diverse basin productivities and production settings (i.e., performance in recovery practices and different technologies). The category *wells under construction* is associated with the stages well pad development, trucks and water pipelines, drilling, fracking and well completion, while the *producing wells* is associated with the stages gas produc-

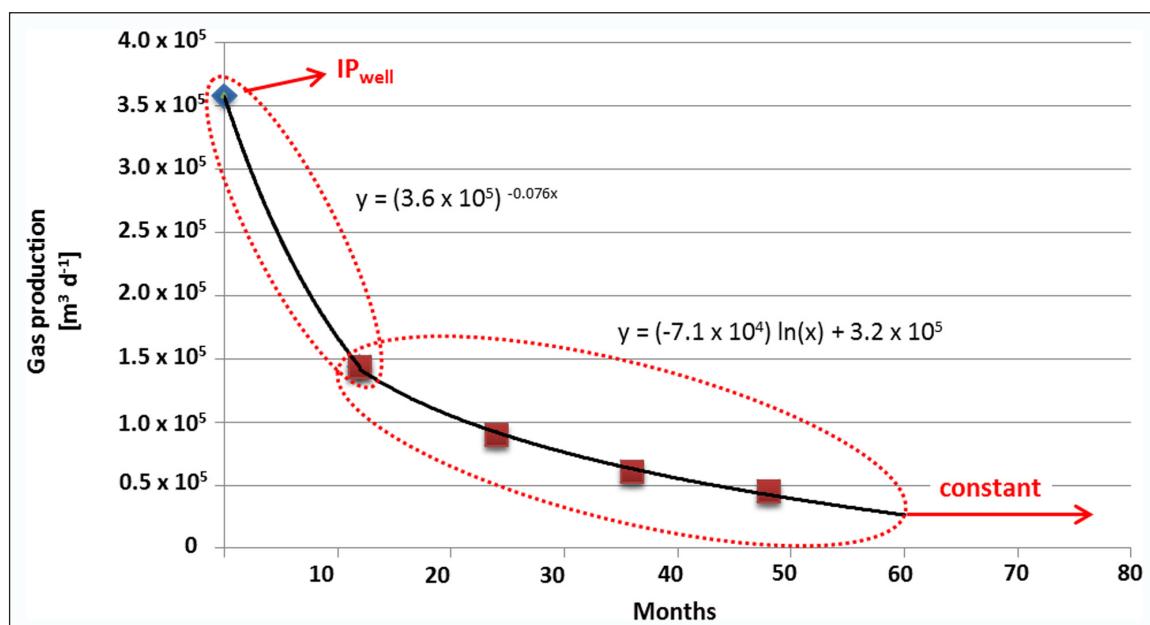


Figure 3: Example of well declining production curve in our scenarios – Unterkarbon (Germany), P50. The declining curve, extrapolated from the Eagle Ford and Barnett shale plays in the US and tailored to the EUR and IP of our case study reservoirs, follow an exponential trend in the first year, and a logarithmic trend in the following 4 years (see equations in the figure). From the 5th year onwards, we assume that production remains constant. DOI: <https://doi.org/10.1525/elementa.359.f3>

tion, wellhead compressor exhausts, liquids unloading, gas gathering and processing. Emissions are calculated by combining activity data and emission factors for each stage of shale gas production, depending on the technology and uncertainties associated with each specific scenario. Activity data represent the magnitude of activity that results in emissions, while emission factors represent the gas released per unit of a given activity, and are typically provided as a range. All input parameters are based on official reports, expert support and peer-reviewed publications, most of which focused on US shale gas plays since shale gas production has hitherto mostly occurred there. Additionally, the input parameters include our own critical assessments of how to best apply the data to the European cases proposed in this study (described in further detail in SM, Text S1 Section S2). Where available, we opted for large sample-size surveys, with a preference for results by accredited research groups such as the Environmental Defense Fund (EDF, 2019). A list of the parameters and variables that determine emissions as well as the reference literature is reproduced in **Table 2**. To realistically assess VOC emissions as a by-product of natural gas production, we also varied the VOC component of natural gas to examine the impact of both wet and dry gas on total VOC emissions according to gas composition reported by Faramawy et al. (2016).

Our emission scenarios are divided into two overarching categories based on varying technologies/performances at each stage of gas production, namely “realistic” and “optimistic” emission scenarios (abbreviated as REm and OEM). REm refers to practices and standard technologies used for gas exploitation and management which generate relatively high emissions (i.e., business as usual), and are still largely used in the US and Europe. This case is considered the realistic case that we expect for the two European countries examined. On the other hand, OEM refers to the

challenging case where emission reduction technologies (e.g., electric motors instead of diesel-engines) and all best practices and monitoring services are in place and fully employed across the supply chain (e.g., no damages of any component, no malpractice and abatement of unwanted gas losses). This case is defined as the most optimistic case and represents the lowest technical emission boundary achievable according to the technologies and practices considered in this study and described in detail in **Table 3** and SM Text S1, Section S2. REm and OEM illustrate the degree to which these two different cases can affect emissions of the suite of pollutants and GHGs under study, and they provide a clear indication on possible mitigation potential of different options. Obsolete technologies or practices that we expect not to be permitted in Europe are not considered in any scenario: e.g., open-air pits, improper well completions (SM Text S1, Section S2.6), low number of wells per pad (SM Text S1, Section S1.1), insufficient environmental standards during the liquids unloading practice (SM Text S1, Section S2.9), lack of recycling of fracking/drilling waters (SM Text S1, Section S2.3), and so forth. These scenarios are informative for evaluating best recovery practices to outline new environmental regulations for drilling and producing. The main technologies and operations that differentiate REm and OEM are listed in **Table 3**, while a complete description is available in SM Text S1, Section S2.

Due to data uncertainty and unpredictable intrinsic variables (e.g., number of fracking stages, uncertainty in values reported by the source agency, etc.), a range of emissions are developed for REm and OEM. Therefore, both scenarios can be further broken down into “upper” (U) or “lower” (L) categories that define the ranges of uncertainty. “U” results define the high end of the emission range, while “L” results define the low end. Altogether, this produces four scenarios (from the lowest to the highest emissions):

Table 2: List of parameters and variables defining emission variations between REm and OEM. Sources of data are also provided. Note that EF stands for emission factor. DOI: <https://doi.org/10.1525/elementa.359.t2>

Activity	Parameters/variables defining emission scenarios	Source of reference
Well pad development	Length of operations, EF diesel motors	NYSDEC (2015); Helms et al. (2010); European Emission Standards. ²
Truck Traffic	EF of truck motors, re-suspended particles, road type; materials, water and chemicals supply, waters recycle rate and “piped” vs. “trucked” rate, average well length, fracking stages.	IVT (2015), NYSDEC (2015); EMEP/EEA (2016); Denier Van Der Gon et al. (2018); Statista; CottonInfo (2015).
Drilling	Diesel generators vs. electricity; total wells length.	Pring et al. (2015); Helms et al. (2010).
Fracking operations	# fracking stages, length of operations, diesel engines EFs.	Roy et al. (2014); Helms et al. (2010).
Well completion	Emissions at operations.	Allen et al. (2013).
Production sites	Diesel vs. electric compressors, gas emissions at facility.	Omara et al. (2016); ICF (2014).
Wellhead compressors	Diesel/electric compressor.	NYSDEC (2015); Helms et al. (2010).
Liquids unloading	Automatic vs. manual plunger lifts, operations per well	Allen et al. (2015)
Gathering facilities and pipelines	Gas loss at facility, number of wells connected to the facility, gas loss from pipelines	Mitchell et al. (2015); Marchese et al. (2015); Helms et al. (2010);
Processing	Gas loss at facility, gas turbine efficiency	Mitchell et al. (2015); EPA (2000); Müller-Syring et al. (2016)

OEm-L, OEm-U, REm-L and REm-U. To visualize the breadth of our scenarios, we have represented them as a three-dimensional cube in **Figure 4**.

Results and discussion

GHG emissions in shale gas scenarios

In this section we examine annual emission results from all the scenarios developed in this study and extensively described in the methodology section and SM Text 1 sections S1 and S2. We discuss results under the two technological/performance settings employed during shale gas development (REm and OEm), under differing well produc-

tivities (P25, P50 and P75), for both wet and dry gas, for different GHGs and air pollutants, and for both countries under study (Germany and the UK). Both CH₄ and CO₂ emissions from our shale gas scenarios display significant differences in REm and OEm in both countries. In the following paragraphs we focus on wet gas scenarios, while we refer to dry gas scenarios only occasionally: emission trends from dry scenarios closely resemble those from wet scenarios, with the exception that VOCs make up a very small component of the gas composition. Total CH₄ released in REm ranges between 104 and 175 Kt in the UK, and between 46.4 and 78.5 Kt in Germany in the P50 cases (**Figure 5**).

Table 3: List of major differences in the technologies applied to REm and OEm scenarios. DOI: <https://doi.org/10.1525/elementa.359.t3>

Activity Data	REm	OEm
Motor type	Diesel-engines are used during all stages. Emission factors for non-road diesel machineries refer to the inventory from the German Environmental Agency (Helms, 2010).	Electrified motors applied at some of the production stages at gathering. Emission factors for the national electric grid are available from the German Environmental Agency (UBA, 2017) and are applied to Germany and the UK.
Fracking waters management	Fracking waters are transported to the well site via trucks, with low recycling rates (50%). Emission factors for trucks (Euro3/6) are available from the IVT database (IVT, 2015).	All fracking waters are piped to the well site, with high recycling rates (90%). Emission factors for trucks (Euro6) are available from the IVT database (IVT, 2015).
Turbines (processing)	The volume of gas combusted to fulfil energy requirements during processing is calculated according to the efficiency and performance of a simple cycle, uncontrolled turbines.	Volume of gas combusted to fulfil the energy requirement during processing is calculated according to the efficiency and performance of a combined cycle, water steam-injection turbines.
Emission factors	Emission factors for all engines categories are conservative.	Emission factors for all engines categories follow recent, strict national, legally-binding emission standards.
Well structures	Well ramifications (horizontal wells) at the bottom of each vertical well: 3.	Well ramifications (horizontal wells) at the bottom of each vertical well: 10.

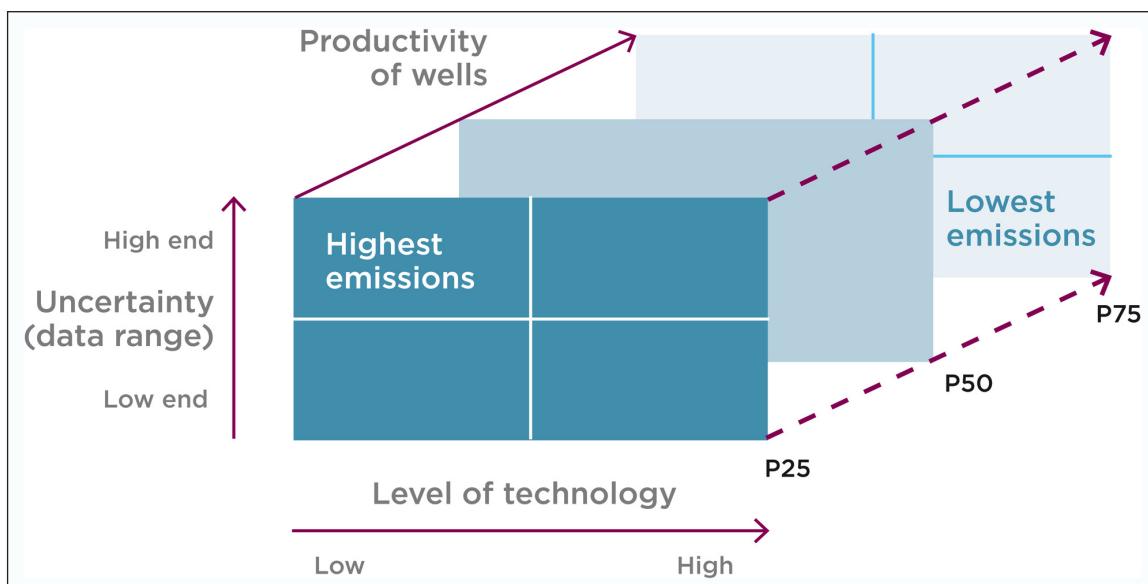


Figure 4: 3D cube representation of shale gas emission scenarios. On the x-axis is the level of technology which is based on the level of regulation; the y-axis represents the uncertainty range in the data, and the z-axis represents the productivity of the wells from the three drilling projections (i.e., P25, P50 and P75). DOI: <https://doi.org/10.1525/elementa.359.f4>

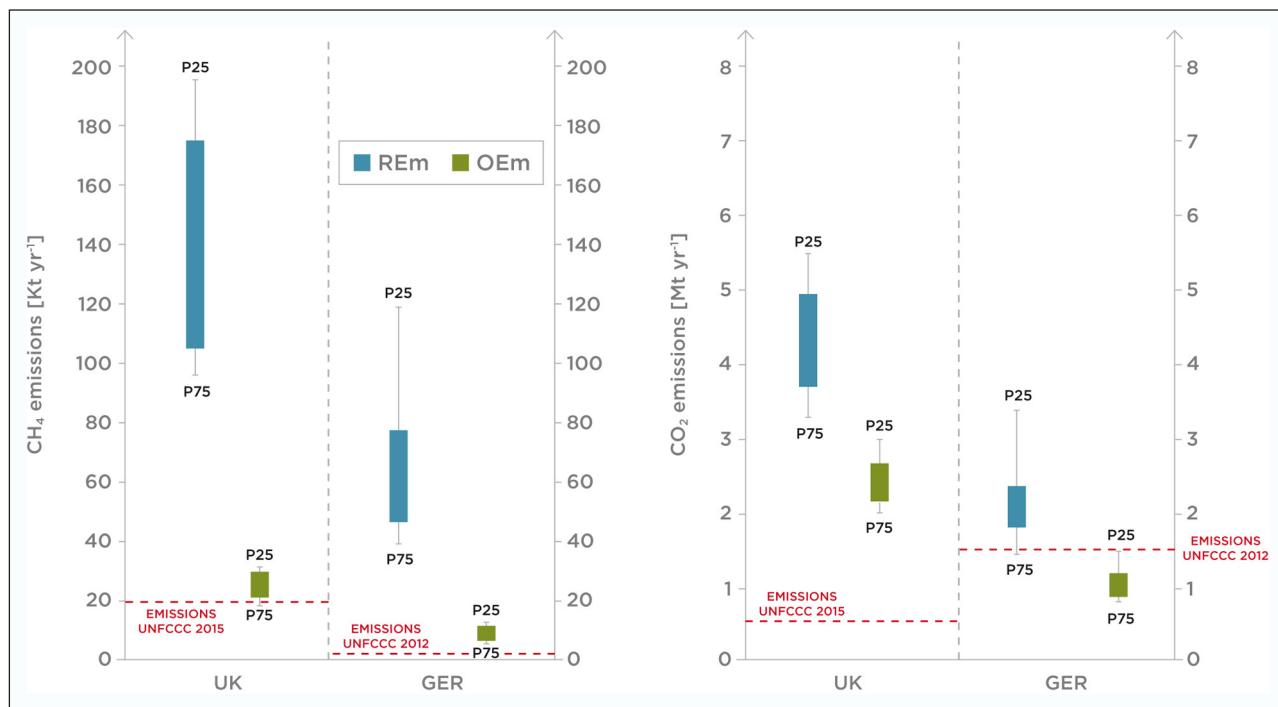


Figure 5: CH_4 and CO_2 annual emissions from our study for Germany and the UK. The dot lines in red represent the emission volumes as reported by the UNFCCC for the year reported. DOI: <https://doi.org/10.1525/elementa.359.f5>

On the other hand, under the P25 well productivity case maximum CH_4 emissions reach 196 and 119 Kt for the UK and Germany respectively, while in P75 values are not significantly lowered beyond the P50 case. Low well productivity therefore translates into significantly enhanced CH_4 emissions, especially in Germany. The wells' steep production curve characterizing shale reservoirs overall, along with lower volumes of recoverable gas in this specific case justify the higher drilling rate necessary to maintain production constant. The resulting larger population of active wells in both categories *producing wells* and *wells under construction* are ultimately responsible for augmented emissions. On the contrary, CH_4 losses generated by OEM are significantly lower and within a narrow range among the different productivity projections. Here the ranges are from 21.5 to 31.3 Kt for the UK, while from 7.4 to 11.0 Kt in Germany. CO_2 emissions in REm range from 3.7 to 4.9 Mt in the UK and 1.8 to 2.3 Mt in Germany under the P50 scenario case. While low well productivity in REm increases emissions in the UK to a maximum of 5.5 Mt, in Germany the increase is proportionally higher reaching almost 3.4 Mt. CO_2 emissions in OEM range between 2.2 and 2.7 Mt in the UK (P50), and between 0.9 and 1.2 Mt in Germany (P50). The distribution of GHG emissions across the production stages and their variability under different technological/performance cases and for each country are shown in **Figure 6**.

In the following discussion we focus on results from the P50 scenarios, with reference to the other productivity cases when significant emission variations warrants further analysis. Nevertheless, the emission boundaries for our scenarios are reported in all diagrams displayed in **Figure 6** to represent the range of variability in our

results: OEM-L P75 and REm-U P25 for the lower and upper bounds, respectively. CH_4 released during well preparation stages (i.e., excavators, well pad configuration and construction) are trivial when compared with total emissions generated by the whole chain. From well construction up until hydraulic fracturing (i.e., drilling activities, water, sand and equipment moved by trucks, fracking and well completion) a maximum of 0.5 Kt CH_4 for both countries are lost over the entire year, mostly concentrated at well completion. Strict emission mitigation measures deployed in the OEM can facilitate reductions by a maximum of circa 50%. CH_4 leaked or vented by compressors, valves, joints and gaskets, represents an important contributor under REm (19 to 33 Kt in Germany, 62 to 108 Kt in the UK), while consolidation of wells onto centralized well pads (more horizontal wells per vertical well; see also Robertson et al., 2018) combined with substitution of diesel engines with electrically-powered ones as foreseen in OEM limits losses at production site to ca. 3 and 11 Kt in Germany and the UK, respectively. Since uncombusted gas and wet seals in diesel and natural gas-powered compressors are the main sources of fugitive CH_4 , replacement with electric compressors can eliminate emissions (Kirchgessner et al., 1997; Marchese et al. 2015 Supporting Information; Mitchell et al., 2015 Supporting Information). Similar reductions (of ca. 95%) can be achieved by implementation of dry-seal compressors with flaring systems (EPA, 2014b).

Wellhead compressors and liquids unloading (both with manual or automatic plunger lifts) have a very limited impact on total figures. The former are employed to increase the gas yield from low-pressure reservoirs, while the latter is a practice necessary to unclog the wells when

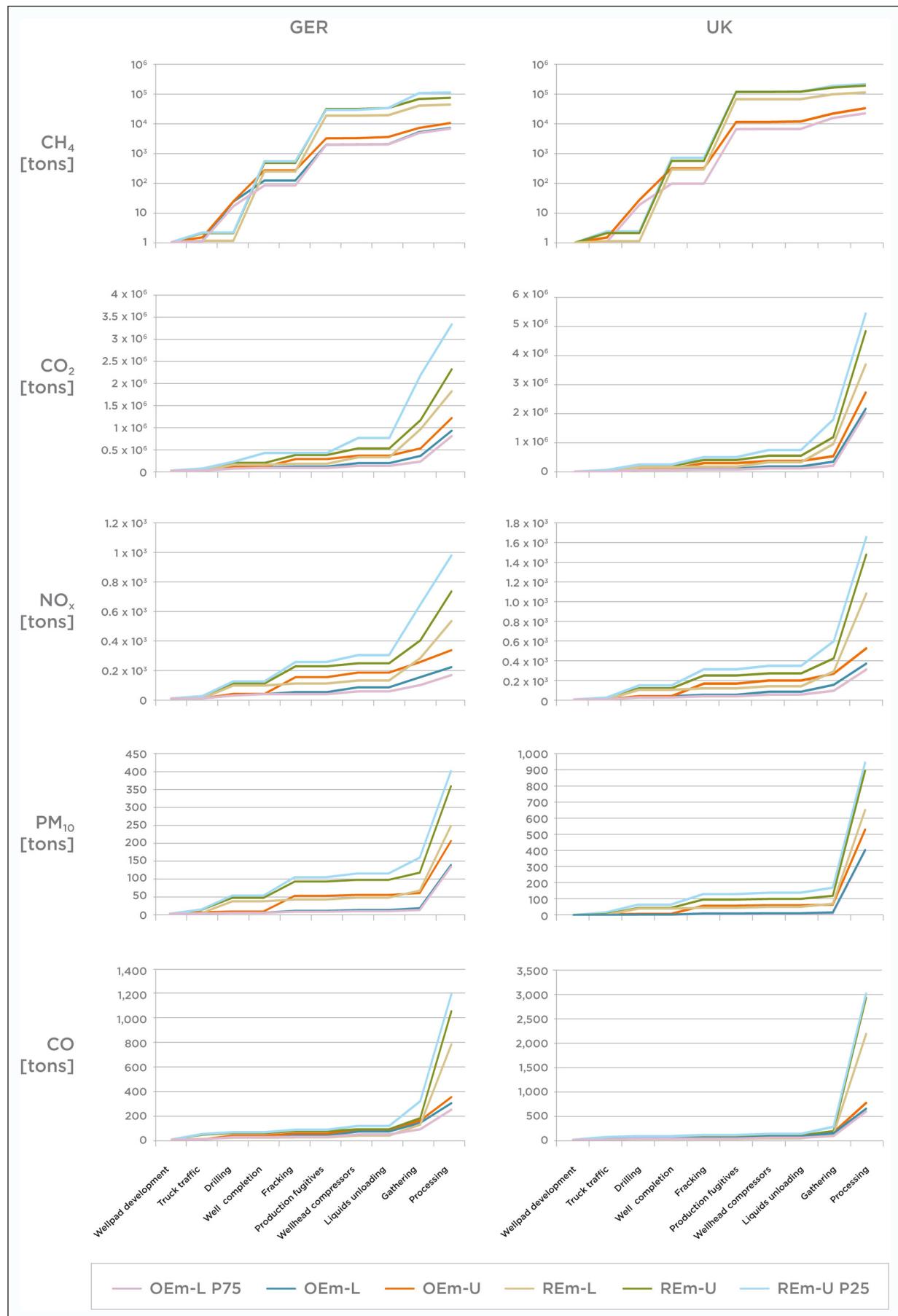


Figure 6: Annual cumulative emissions along the shale gas production chain. Results for CH_4 , CO_2 , NO_x and PM_{10} for Germany (GER, left) and the UK (right). REm and OEM are shown for the P50 case, while REm-U P25 and OEM-L P75 are also reported to show the emission boundaries. DOI: <https://doi.org/10.1525/elementa.359.f6>

large amount of liquids accumulate in the borehole. At the gathering stage, regardless of how compressors are operated, CH₄ losses (which include both gathering pipelines and gathering facilities, SM Text S1, Section S2.10) represent 35–48% of total emissions generated by the scenarios in Germany, and 24–41% in the UK. Here again, mitigation measures applied in OEM appear to be effective, decreasing CH₄ emissions by as much as 87% to 88% in Germany and 83% to 87% in the UK (low and high emissions boundaries, respectively). Because of the high emission factor associated with each gathering facility (Marchese et al., 2015; Mitchell et al., 2015) and also enforced in our emission exercise, reducing the number of gathering facilities collecting the gas from the production areas appear to contribute significantly to reduced gas losses. The number of these facilities is strictly linked to the geographical location of the *producing wells*, and to the technical feasibility and economic convenience to connect them to a single (large) or more (smaller) gathering plants. We assume one gathering facility for every 30 wells in REm, and one for every 80 wells in OEM (SM Text S1, Section S2.10.1). In the latter, emissions are mainly controlled by substitution of diesel to electric engines.

At gathering facilities, emission factor standards for diesel engines have negligible effects, while gas losses combined with the number of gathering facilities dominate this gas production stage contributing up to circa 90% in Germany and 70% in the UK of total CH₄ emissions. On the other hand, emissions from gathering facilities in OEM are significantly lower (circa 10% of CH₄ emitted in REm for Germany and between 20 and 30% for the UK), where gathering pipelines contribute to more than 65% in Germany and 87% in the UK of total CH₄ emissions in the gathering sector. It is worth noting that in REm-U P25 scenarios CH₄ emissions from gathering are particularly higher than the ones in P50 (50% higher in Germany and 35% in the UK), highlighting the impact that low well productivity (especially in Germany) has on gathering sector emissions. The prominent role of CH₄ emitted at gathering facilities and production sites finds confirmation in the literature (Zavala-Araiza et al., 2015; Balcombe et al., 2016; Littlefield et al., 2017). The gas processing stage, as characterized in our study (between 2.8% and 5.6% of gas burned for power production and turbines efficiency between 30% and 60%; SM Text S1, Section S2.11.2), comes only third in terms of CH₄ emissions contribution after the gathering and production stages in REm, while second in OEM. This is because best practices aiming to reduce the overall losses from processing plants are able to drive emissions down by about 50% overall. Other factors such as turbine efficiencies, combusted gas for energy needs and emission factors are, for this pollutant, irrelevant for both countries and scenarios. Gathering and processing of shale gas dominate total CO₂ emissions in all scenarios, spanning from 55% in OEM to 70% in REm. Mitigation measures such as electrification of all compressors and pumps applied in OEM at gathering facilities are particularly efficient to cut gas losses at this stage by ca. 75% in both countries. Similarly, the amount of gas burned to produce electricity and fulfil the energy needs

at this stage – mainly driven by turbine efficiencies – can potentially reduce emissions between 30 and 40%. Well-head compressors and fracking are next in order of importance although they only account for 2 to 15% of total CO₂ emissions in almost all scenarios for both countries.

GHG emissions national contexts

Here we compare our results of GHG emissions from shale gas with emission inventories supplied to the United Nation Framework Convention of Climate Change (UNFCCC) for the energy industrial system (i.e., power and heat production, petroleum refining and manufacture of solid fuels). For this scope, we select the year 2012 for Germany and 2015 for the UK as reported in the National Inventory Report (NIR) year 2017 submission, since the conventional gas domestically produced in these years is similar to the ones assumed in the scenarios: 10.7 bcm for Germany and 34.4 bcm for the UK.³ Focusing on the UK, CH₄ and CO₂ generated by the well-preparation stage till processing (namely, upstream) of the current natural gas industry only contributed 7.0% (CH₄) and 0.4% (CO₂) of total emissions from the industrial energy sector for the UK. For the former, shares from the OEM P50 scenarios of total gas released from the energy sector are similar in magnitude, while emissions under REm P50 settings achieve 30 (REm-L) to 65% (REm-U) of reported current datasets for the UK (up until 70% under P25). All results are reported in **Table 4**. Most of the offshore gas produced in the UK requires processing (UNFCCC, NIR for the UK, year 2017 submission) due to its variable but still notable content of impurities like CO₂, nitrogen, ethane, and so on (Cowper et al., 2013). The conservative emission estimates from the current UNFCCC Report may be justified assuming that best practices for CH₄ capture are all in place and properly performed, keeping them down to a level comparable with the lowest depicted by our scenarios. On the other hand, the CO₂ relative contribution to emission from the energy industry raises from 0.4 to 1.6% when comparing results from the UNFCCC Report with OEM or until 3.5% with REm. Therefore, even under our most conservative scenario contemplating the highest combustion turbine efficiency and the lowest combustion rate of gas during high-emitting processing activities, CO₂ emissions reported by the UNFCCC are about one fourth of these. In Germany, CH₄ emitted from the natural gas upstream system contribute about 0.6% of the total emitted by the national energy system, while CO₂ only 0.4%. This is mostly due to the high consumption of solid fuels in the country that brings coal (and lignite in particular) far to the top of the list of emitters: CO₂ released from natural gas combustion are similar for the two countries, while those generated in Germany by solid fuels are four times more than in the UK (UNFCCC, NIR submission 2017 for both countries). CH₄ emissions produced by our scenarios raises contributions to a range of 1.6 to 2.4% of total energy from the industrial system emissions in OEM, and up to 10.3%–17.4% in REm. This means that the natural gas sector is an important contributor requiring appropriate attention by regulators when prescribing technologies, monitoring and verification systems, in Germany

Table 4: Annual CH₄ and CO₂ emissions generated by our shale gas industry for Germany (GER) and the UK.

Results are compared with emissions of the current upstream natural gas chain and the energy (heat and power) sector as described by the UNFCCC. Please note that the term “fugitive” in the UNFCCC reference relates to all methane emissions associated to that specific stage. DOI: <https://doi.org/10.1525/elementa.359.t4>

Species	Fuel combustion emissions – Energy industry (UNFCCC, 2017). In Kt.	Fugitive emissions fossil fuels (UNFCCC, 2017). In Kt.	Emissions gas upstream (UNFCCC, 2017) and share	OEm P50 results as share of current emissions (Range boundaries). In Kt.	REm P50 results as share of current emissions (Range boundaries). In Kt.
GER CH ₄	89.9	366	2.7 (0.6%)	7.4 (1.6%) to 11.0 (2.4%)	46.4 (10.3%) to 78.5 (17.4%)
GER CO ₂	359,000	2960	1590 (0.4%)	924 (0.3%) to 1213.0 (0.3%)	1830 (0.5%) to 2330 (0.6%)
UK CH ₄	12.1	258	19.5 (7.0%)	21.5 (7.9%) to 31.3 (11.6%)	104 (30%) to 175 (65%)
UK CO ₂	133,000	4560	514 (0.4%)	2,190 (1.6%) to 2,750 (2.0%)	3,726 (2.7%) to 4,880 (3.5%)

as in the UK. On the other hand, CO₂ generated by the German shale gas industry maintain emissions from 0.2 to 0.6% (**Table 4**), to a maximum of 0.9% in the REm P25.

Of total gas produced in Germany, 40% has high sulfur content (sour gas) that has to be discarded by specific treatments before the gas can access transmission lines. In the UNFCCC NIR submissions 2017 for Germany, CO₂ and CH₄ emission factors for removing sulfur are 336 and 0.11 kg per 1,000 m³ of treated gas respectively. The only CO₂ and CH₄ emissions associated with the processing stages of gas reported are those related to the treatment of sour gas, while no other emissions attributed to pre-treatments occurring at pumping stations (such as water, hydrocarbons and solid removals), are listed. We therefore assume that in the current gas extraction industry, no CO₂ or CH₄ emissions are associated with, or rather expected from, pre-treatments, an aspect for which we believe deserves further investigation into the reliability of such an assumption.

Despite the relevance of discussing our results in the context of national inventories, it is challenging to explain the inconsistency in the results for REm (and from the US) with the emissions reported for Germany and the UK under the UNFCCC. A study of CH₄ emitted from the Groningen field in the Netherlands by Yacovitch et al. (2018) also struggled to provide an explanation for the large emission discrepancy between their campaign observations and national inventories. The authors of the same study believe that major differences between North American and European estimates cannot be ascribed to the large-scale adoption of hydraulic fracturing in the former. Riddick et al. (2019) also report high and unreported CH₄ losses from oil and gas wells in the North Sea, criticizing bottom-up methods and self-reporting by operators as an improper practice. Our findings displayed in **Figure 6** also show that emissions generated at stages that are specific to shale gas activities (i.e., well completion and fracking) have only a minor effect on total CH₄ losses when RECs are in place (SM Text 1 Section S2.5 and S2.6). Most critical CH₄ and air pollutant sources across the gas chain have been attributed to above-ground mal-practices, failures or malfunctions unrelated to the gas nature (i.e., conventional or shale gas), as reported by the

studies produced by the Environmental Defense Fund initiative and others (Sauter et al., 2013; Elsner et al., 2015; Omara et al., 2016; Atherton et al., 2017). Based on the latest evidence, gas capture solutions, “detection and repair” services, as well as monitoring and early detection of super-emitters are the most likely key measures when it comes to effectively mitigate emissions for both gas sources (EPA, 2014a; Westaway et al., 2015; Ravikumar and Brandt, 2017; Zavala-Araiza et al., 2017; Konschnik and Jordaan, 2018). Unfortunately, surveys that investigate European CH₄ losses in a transparent and systematic way (e.g., peer-reviewed articles published by independent research bodies) do not exist or are not publicly available, raising doubts over the accuracy and objectivity of emission estimates provided to the UNFCCC (EC, 2015; Larsen et al., 2015; Cremonese and Gusev, 2016; Riddick et al., 2019). To facilitate identifying CH₄ emissions specifically from a future European shale gas industry, for instance Visschedijk et al. (2018) propose an atmospheric ethane monitoring system. Because of these research gaps, we find it hard to justify such a large discrepancy by citing technological, regulatory or geological factors alone. The results shown in OEm are instead much more similar to European national inventories. Namely, the leakage rate as calculated by data from the UNFCCC NIRs is as low as 0.02% for Germany and 0.08% for the UK. Based on our discussion and results, these estimates may be justified by systematic employment and application of best technologies/performances across each stage of the preparation and supply gas chain – a rather unlikely circumstance. Given the fact that there is no transparent information available on the quality of these estimates, we speculate that they could be based on very optimistic assumptions (i.e., as the ones we apply in OEm) instead of systematic and integrated monitoring campaigns (see also discussion in Riddick et al., 2019).

CO₂ and CH₄ contribution to total GHG emissions

The warming-related contribution of CH₄ – a much more potent GHG than CO₂ – is subject to the time frame of observation. This effect is controlled by the oxidation of CH₄ to CO₂ ($t_{1/2} \sim 12$ years; Myhre et al., 2013), so that its warming component in the atmosphere decreases

with time. Two Global Warming Potentials (GWPs) are commonly used in the scientific community: the GWP₁₀₀ and GWP₂₀, with the numbers referring to the warming implications over those periods of time, respectively 20- and 100-years (IPCC, 2014). While these two parameters are complementary and can offer a comprehensive overview on the implications of this pollutant in the short- and long-term, one indicator may be preferred instead of the other according to the scope of a specific research exercise (Ocko et al., 2017; Balcombe et al., 2018). Total aggregated GHG emissions (CO₂-eq) from the shale gas upstream sector and covering all well productivity cases are shown in **Figure 7**, applying both 20- and 100-year periods.

On a mass-to-mass basis, CO₂ emissions are significantly higher than CH₄ because of the large amount of natural gas combusted to CO₂ at processing plants to fulfil the power demand (SM Text S1, Section S2.11.2). Our aggregated upstream shale gas industry displays much higher variability between REm and OEM, than between analysis under GWP₂₀ and GWP₁₀₀. Results in OEM are comparable and between 3.8 and 5.3 Mt y⁻¹ (minimum values of their ranges), while much higher in REm: between 19.6 and 36.0 Mt y⁻¹ (maximum values of the ranges).

CH₄ represents a major contributor accounting for more than 50% of total CO₂-eq. when attributing a GWP₂₀ under

all scenarios (with a peak of 76%), while between 22 and 55% assuming a GWP₁₀₀. REm and OEM differ based on the performance of practices and implementation of diverse technologies to monitor and control CH₄ losses on the one hand, and to increase efficiency of engines and compressors so as to curb emissions of CO₂ on the other hand. It is evident here that, although CO₂ emissions can be cut up to ca. 60% (difference between the REm and OEM CO₂-bars in both GWP scenarios), CH₄ reduction measures are by far more effective and can technically reduce CO₂-eq. CH₄ emissions by 92%. Full compliance with the overall settings applied in OEM has notable climate benefits on reducing aggregated CO₂-eq. volumes by a factor of maximum 5 in the GWP₁₀₀ case, and by a factor of maximum 7 in the GWP₂₀ case.

Methane leakage rates in the international context

Figure 8 shows the CH₄ losses already reported in **Figure 5**, in relation to overall CH₄ production and expressed in percentage for all productivity and technological scenarios. Accordingly, CH₄ emissions from associated activities are not considered here. The Figure also illustrates the effect of different operation and technologies/performances on final leakage rates, the large variance within the OEM range, and the strong correlation between well productivity (the P-cases) and the extent of CH₄ emissions (see in particular Germany OEM P25). Although the leakage rates resulting from our emission scenarios vary considerably, results in REm are within the range of the estimates reported by the latest regional and nationwide studies carried out worldwide (Littlefield, 2017; WEO, 2017; EPA, 2018), or are of similar magnitude (Zavala-Araiza et al., 2015; Alvarez et al., 2018).

Studies based on single measurement campaigns (cross-sectional data) or focused on restricted areas may be inappropriate as a basis of comparison to nation-wide or nationwide emission estimates such as our results. Based on the results of Zavala-Araiza et al. (2017), a skewed emissions distribution generated by the irregular occurrence of super-emitters implies local leakage rates that are inconsistent (i.e., lower in the case that no super-emitters exist in a restricted area or higher if they are over-represented) with the mathematical mean representing a larger area under analysis. Skewed distribution might be caused by the age of a restricted population of wells (see, for example, Omara et al., 2016) or by lax state regulations and poor monitoring campaigns. For this reason, in the following we compare our results with regional or nationwide emission studies. Our scenario results are lower than most estimates from the US: for example, the EPA CH₄ emissions assigned to the gas upstream sector are slightly below the leakage rate of 0.9%, which is similar to the P50 upper value of REm for Germany, but higher than all the results produced by the UK scenarios (up to a maximum of 0.7%; **Figures 8** and **9**). It is here worth noting that the gas vented during well completion practices estimated by the EPA GHG Inventory 2016 are much higher than the amount we assign (SM, Text S1, Section S2.6). Littlefield et al. (2017) carried out a multi-basin analysis on old and new emission data in the US and processed

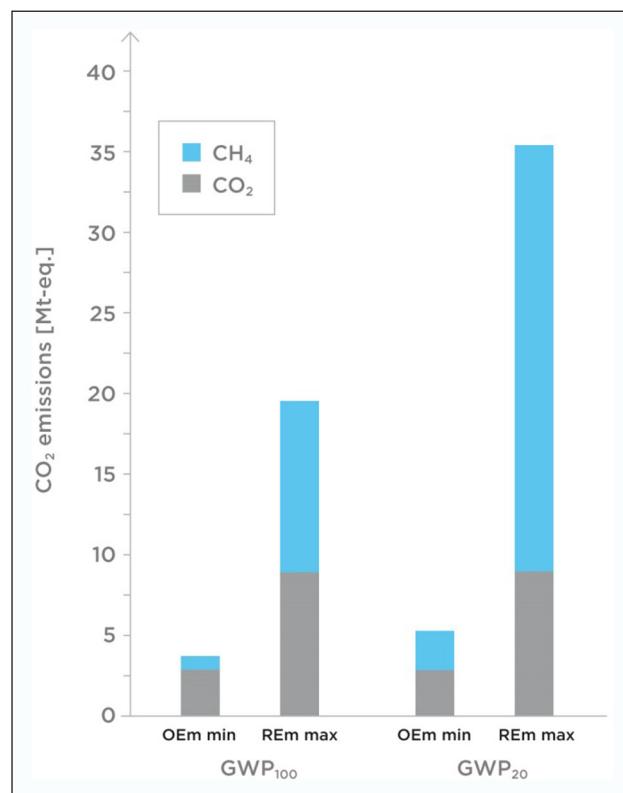


Figure 7: Annual aggregated CH₄ and CO₂ emissions in CO₂-eq. Maximum and minimum aggregated GHG emissions from REm and OEM are relative to all productivity cases (P25, P50 and P75) under different time horizons (GWP₂₀ and GWP₁₀₀). Values refer to emissions produced from well preparation till processing (upstream sector). DOI: <https://doi.org/10.1525/elementa.359.f7>

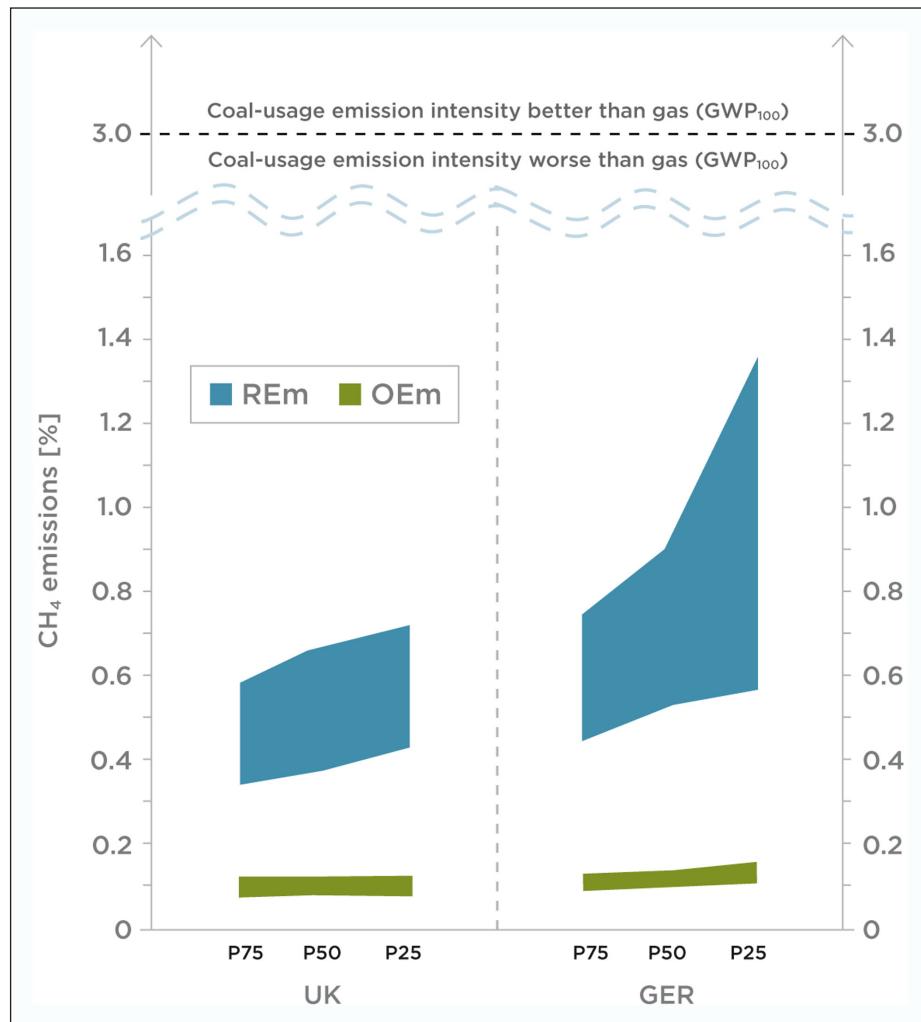


Figure 8: CH₄ leakage rates (in %) for all scenarios for Germany and the UK. The boundary depicted at % leakage: 3% defines the maximum gas leakage rate that still guarantees the climate benefits of gas over coal (WEO, 2017). DOI: <https://doi.org/10.1525/elementa.359.f8>

them in a Monte Carlo simulation to estimate the amount of CH₄ lost along the entire natural gas supply chain. Their study found a leakage rate of 1.23% (with a 95% confidence interval from 0.72 to 1.59%) of the total gas delivered from the wellhead up to the processing stage, a value close to our highest simulated leakage rate (Germany REm P25, **Figure 9**). Zavala-Araiza et al. (2015) estimated an even higher leakage rate at the Barnett gas field – the most investigated gas basin in terms of GHG and pollutant emissions in the entire US – up to 1.5% (confidence interval: 1.2 to 1.9%) as a result of the convergence of top-down and bottom-up measurements within the statistical confidence range.

A recent study that aggregated the results produced by a large number of investigations in the US (Alvarez et al., 2018) estimates national-wide CH₄ emissions from the natural gas supply chain to be 2.3%, with the upstream sector accounting for about 85% of this value (i.e., 1.9%; +0.4/-0.3%). To run the computational model and define nationwide estimates, Alvarez et al. (2018) also included emissions from abandoned wells and flares (with the latter only partially included in our activity data) as well as estimates from studies carried out in different regions.

Their leakage rate is far higher than our highest estimate (i.e., REm-U Germany: 1.36%). In their study, production sites account for ~70% of total upstream CH₄ losses, compared to 30 to 40% in our scenarios. Worldwide, our estimates are consistent with official reports: According to the IEA (WEO, 2017), the average leakage rate in the upstream gas system amounts to 1.14% of total gas produced.

The bottom-up approach employed to develop the emission scenarios (i.e., aggregating process-level emissions) may lead to some relevant emitting sources being overlooked (Brandt et al., 2014), a factor that may partially explain the conservative nature of our results. The technological innovations discussed in the drilling projections, such as the aggregation of 30 wells on single producing pads (not observed in any case study at present), together with the exclusion of forbidden/unexpected gas recovery procedures in Europe can be of help when it comes to interpreting results. Moreover, well productivity – as demonstrated by our results – shows to have a significant influence on total CH₄ emissions. The EUR_{well} across all cases is highly uncertain (i.e., gas-in-place and the TRR have never been empirically tested), and lower values (if

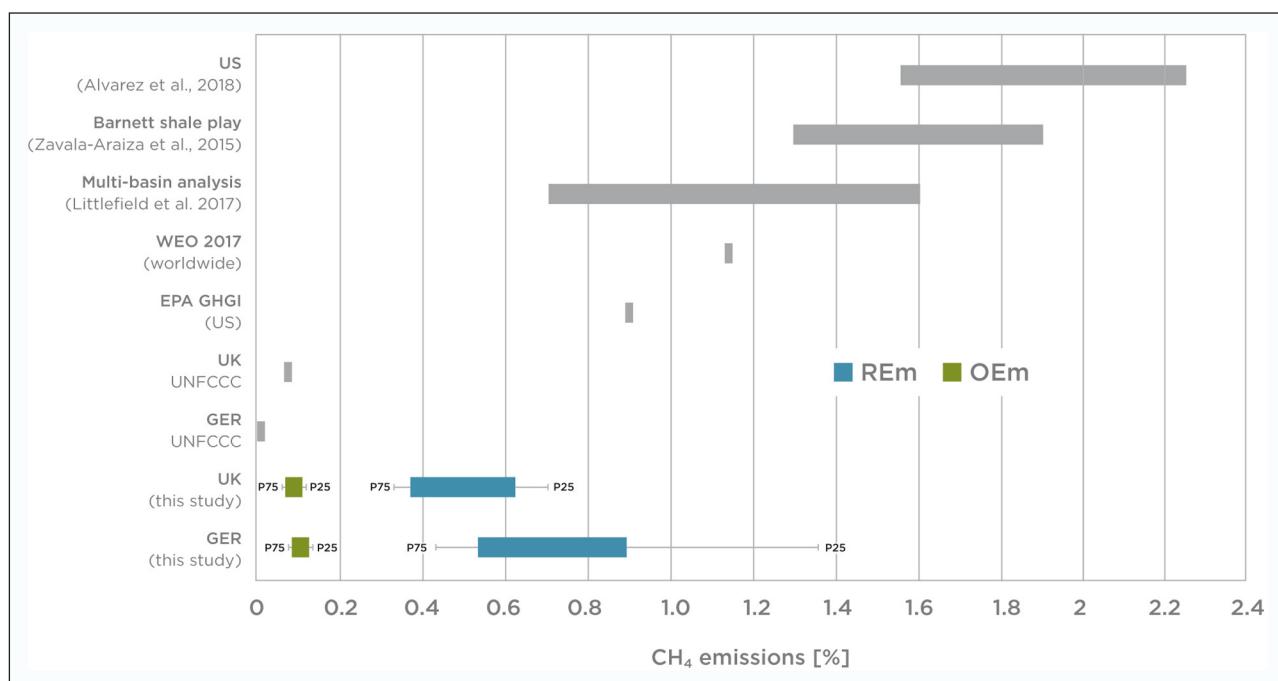


Figure 9: Collection of upstream CH_4 leakage rates of worldwide natural gas systems. The figure includes the most accredited studies investigating CH_4 leakages and compares them with the REm and OEM for shale gas scenarios in Germany (GER) and the UK (Zavala-Araiza et al., 2015; Littlefield et al., 2017; WEO, 2017; Alvarez et al., 2018; EPA, 2018; UNFCCC NIR submission 2018 for Germany and submission 2017 for the UK). All leakage estimates are normalized to the total gas produced, except for Littlefield's study (gas delivered). DOI: <https://doi.org/10.1525/elementa.359.f9>

determined) would surely increase the CH_4 leakage rates found in our study. It is also plausible that the source studies selected to define our emission factors do not wholly and/or comprehensively account for super-emitter contributions. Despite our tailored literature review criteria, this issue is realistic due to the random distribution in space and time of fat tail emissions.

Emission intensity

Despite secondary applications, e.g., the transport sector and homes, most natural gas in Europe is combusted at large power plants to fulfil the electricity and heating demand of households and industry. Its ultimate environmental impact is therefore bound to industrial performance during its extraction, processing, and transformation into accessible energy (e.g., power and heat) and final delivery to the consumers. Based on shale gas emitted from the different scenarios presented in the previous sections, here we determine their emission intensity (EI) in $\text{gCO}_2\text{-eq. kWh}^{-1}$ of electricity produced and discuss how these relate to emissions generated by other sources such as coal, conventional natural gas utilization, and to power production distributed in the German and UK electricity grids (**Figure 10**).

Within a 100-year period, the electrical power EI of a shale gas industry ranges between 394 and 403 $\text{gCO}_2\text{-eq. kWh}^{-1}$ in OEM (5.3% variability), and between 416 and 456 $\text{gCO}_2\text{-eq. kWh}^{-1}$ in REm (12.6% variability). This discrepancy is more pronounced under a 20-year period: the same EI varies from 400 to 412 $\text{gCO}_2\text{-eq. kWh}^{-1}$ in OEM (4.8% variability) and from 443 to 517 $\text{gCO}_2\text{-eq. kWh}^{-1}$

kWh^{-1} in REm (16.7% variability). Gas databases from North America show that gas compositional ranges are unrelated to the gas nature (i.e., conventional vs. unconventional gas), so we can fairly assume the same energy potential when transforming these two types of gas to electrical grid power. Efficiency in overall German gas power plants is nowadays 53% after disaggregating the heat energy component (Icha and Kuhs, 2018). Our power EI results showed by REm are slightly lower than Life Cycle Assessment (LCA – a methodology aiming to assess environmental impacts of a product or service during its entire life cycle) data available in the literature on the US (Jang et al., 2011; Stephenson et al., 2011; Burnham et al., 2012; Laurenzi and Jersey, 2013; Skone et al., 2014) and the UK (Stamford and Azapagic, 2014). In fact, our results under REm overlap most of the lower GHG emission ranges reported by these studies. Differently, the emission intensity of shale gas-fired power plants in China is estimated at 625 $\text{gCO}_2\text{-eq. kWh}^{-1}$ (Qin et al., 2017). Nevertheless, due to different impact categories analyzed (broader for LCA exercises) and the unclear EUR of European shale gas wells, the scientific significance of a direct comparison between our EI results and these studies is limited. In 2016, an emission factor of 382 $\text{gCO}_2\text{-eq. kWh}^{-1}$ is attributed to the energy consumed and generated by natural gas in Germany, less than half of what is emitted per kWh by hard coal utilization (847 $\text{gCO}_2\text{-eq. kWh}^{-1}$) and just one-third of the value for lignite (1150 $\text{gCO}_2\text{-eq. kWh}^{-1}$; Icha and Kuhs, 2018). The EI offset between natural gas and coal observed in **Figure 10** well resembles the findings of the natural gas vs. coal intensity explanatory model

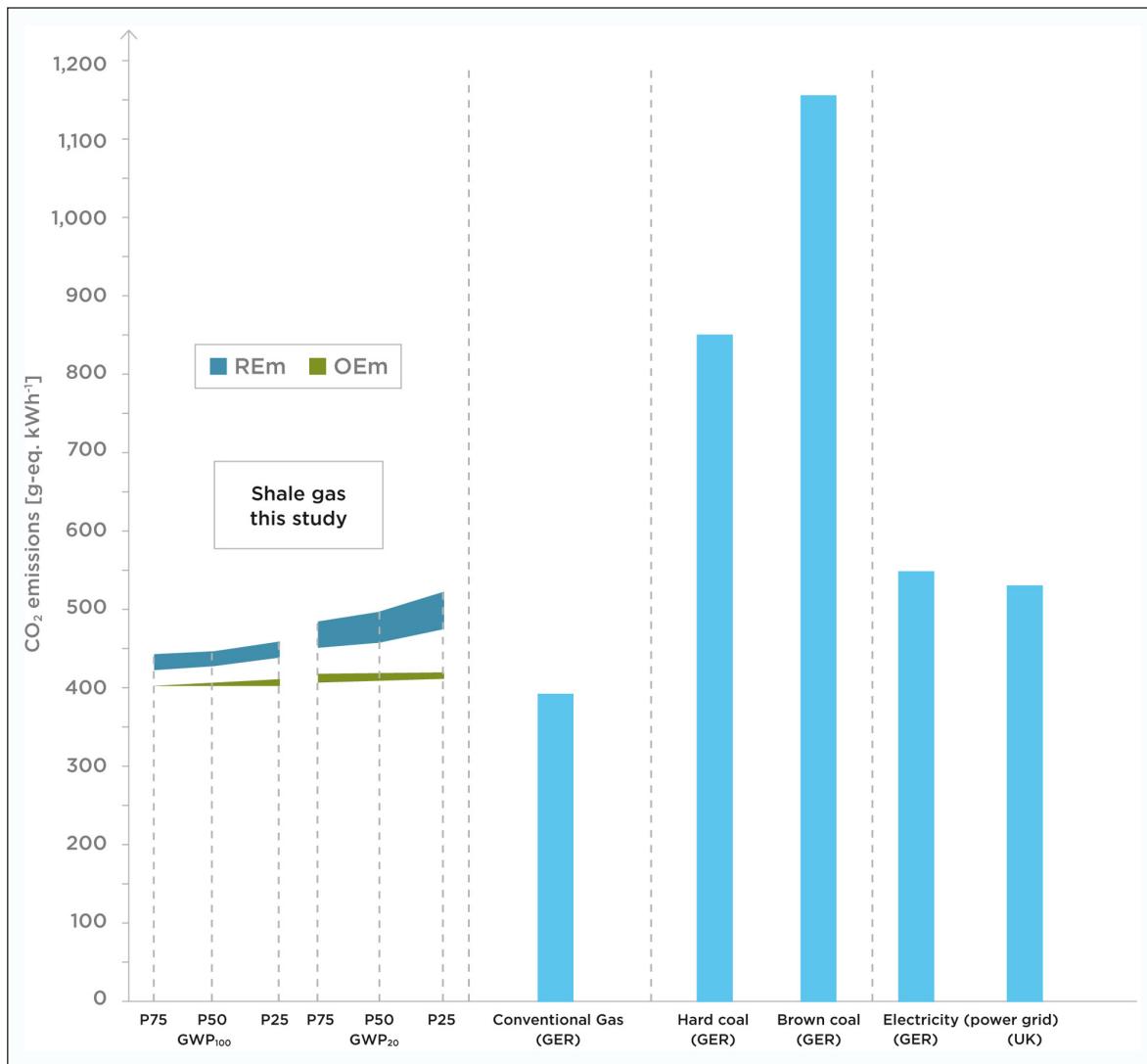


Figure 10: Comparison of emission intensities. Our results are compared with conventional gas (Germany, GER), hard coal (GER), brown coal (GER) and electricity production (GER and the UK). Results are shown in gCO₂-eq. kWh⁻¹. Grid losses are included in all cases. Natural gas energy density: 38.3 MJ m⁻³; Natural gas power turbine efficiency: 53% (Icha and Kuhs, 2018); Average indirect/WTT emission factors for fuels resulting from the production, transport and distribution: BEIS, 2016; Power grid losses: 9% own calculations based on results showed in BEIS (2016). DOI: <https://doi.org/10.1525/elementa.359.f10>

presented by the IEA (WEO, 2017), which illustrates how gas has a stronger impact on the climate compared with coal only at leakage rates above 3% (see **Figure 8**). In China instead, due to inadequate CH₄ recovery at coal power plants, this boundary is about 6% and 12% when attributing a GWP₂₀ and a GWP₁₀₀ respectively (Qin et al., 2017). Similarly, our results on the coal-gas comparison well resemble data from previous studies (Stamford and Azapagic, 2014). Nevertheless, as we critically discussed in a previous section, CH₄ losses associated with current gas production in Germany (see **Figure 5**) and in some of other countries exporting to it (i.e., Netherlands and Norway) are estimated as much lower than the ones forecasted in this study (Larsen et al., 2015; Cremonese and Gusev, 2016), a factor that alone drives the shale gas EI values beyond present national estimates of gas production. Accordingly, the EI of our European shale gas industry appears higher than the one from conventional gas combustion in Germany and the UK, spanning in a range from

3% (OEm-L P75, GWP₁₀₀) to 35% (REm-U P25, GWP₂₀). Moreover, it must be pointed out that CH₄ emissions at Russian producing fields – providing between 40% and 50% of natural gas consumed in Germany – and along Russian-European transmission lines are together responsible for a loss of about 1.3% of the total gas shipped (Cremonese and Gusev, 2016), an aspect that is only partially reflected in the German national emission databases and ultimately to EI estimations. Taking this into account would very likely imply higher natural gas emitted in Germany. For the same reason pertaining to low accuracy and reliability of data, CH₄ losses on transmission lines connecting processing plants and combustion sites in the future European shale gas scenario are not considered in our analysis. Moreover, a future European shale gas industry will necessitate the construction or refurbishment of new pipeline systems in conformity with best standards and environmental regulations available at that point in time. Under the assumption that power plants lie nearby

or within the producing shale gas regions in Germany and the UK, it is reasonable to expect minor losses along these structures that would therefore not affect the shale gas EI to any considerable degree. Taking these plausible assumptions into consideration, including inaccurate estimates of losses along natural gas transportation lines in our emission scenarios would not enhance its overall precision or better reflect reality.

Based on our comparison, EI of a shale gas industry is instead slightly below emissions associated with power production in Germany and the UK, indicating how carbon intensive fossil fuels still dominate emissions in this field despite the expansion of renewables and the still relevant share of nuclear power. At present, power produced in Germany and the UK by the national energy system and distributed by the electricity grid is currently equal to $g\text{CO}_2\text{-eq. kWh}^{-1}$ and $528\text{ gCO}_2\text{-eq. kWh}^{-1}$, respectively. These values include grid losses and are based on original datasets from the Department of Business, Energy & Industrial Strategy (BEIS, 2016) and Icha and Kuhs (2018).

Other pollutants

Volatile Organic Compounds (VOCs)

VOCs are highly-volatile carbon-based compounds which are generated by both natural (biogenic) and anthropogenic sources. Their emissions can be harmful to human

health and the environment due to their role as a precursor in tropospheric (ground-level) O_3 formation. Natural unprocessed gas typically consists of 75–90% CH_4 by volume, while the rest is largely composed of VOCs (e.g., Baker et al., 2008, Gilman et al., 2013, Faramawy et al., 2016). Therefore, when CH_4 leakage occurs stemming from unprocessed gas, this also implies VOC leakage.

It is worth noting that the only difference between wet and dry gas scenario results presented in our study is the amount of VOCs released (i.e., $\text{CH}_4:\text{VOCs}$ ratio in the raw gas), while all other species are unaffected. In the P50 wet scenarios, total VOCs emissions range from 3.8 to 38.5 Kt for Germany, and 10.7 to 85.8 Kt for the UK (**Figure 11**). Due to the notably lower well productivity in the P25 wet scenarios (especially for Germany), VOCs are circa 50% higher (58.3 Kt) in Germany and 12% (96.2 Kt) in the UK when compared with the P50 scenario. In the emissions scenario under P75, VOC losses decrease only minimally compared with the P50 case. As expected, VOC emissions are significantly lower under the dry gas scenarios: for P50, VOC loss ranges from 1.0 to 10.6 Kt in Germany, and 2.9 to 23.6 Kt in the UK (**Figure 11**).

Variations in VOC losses under the P25 the P75 cases for the dry gas scenario are proportional to the wet gas scenario.

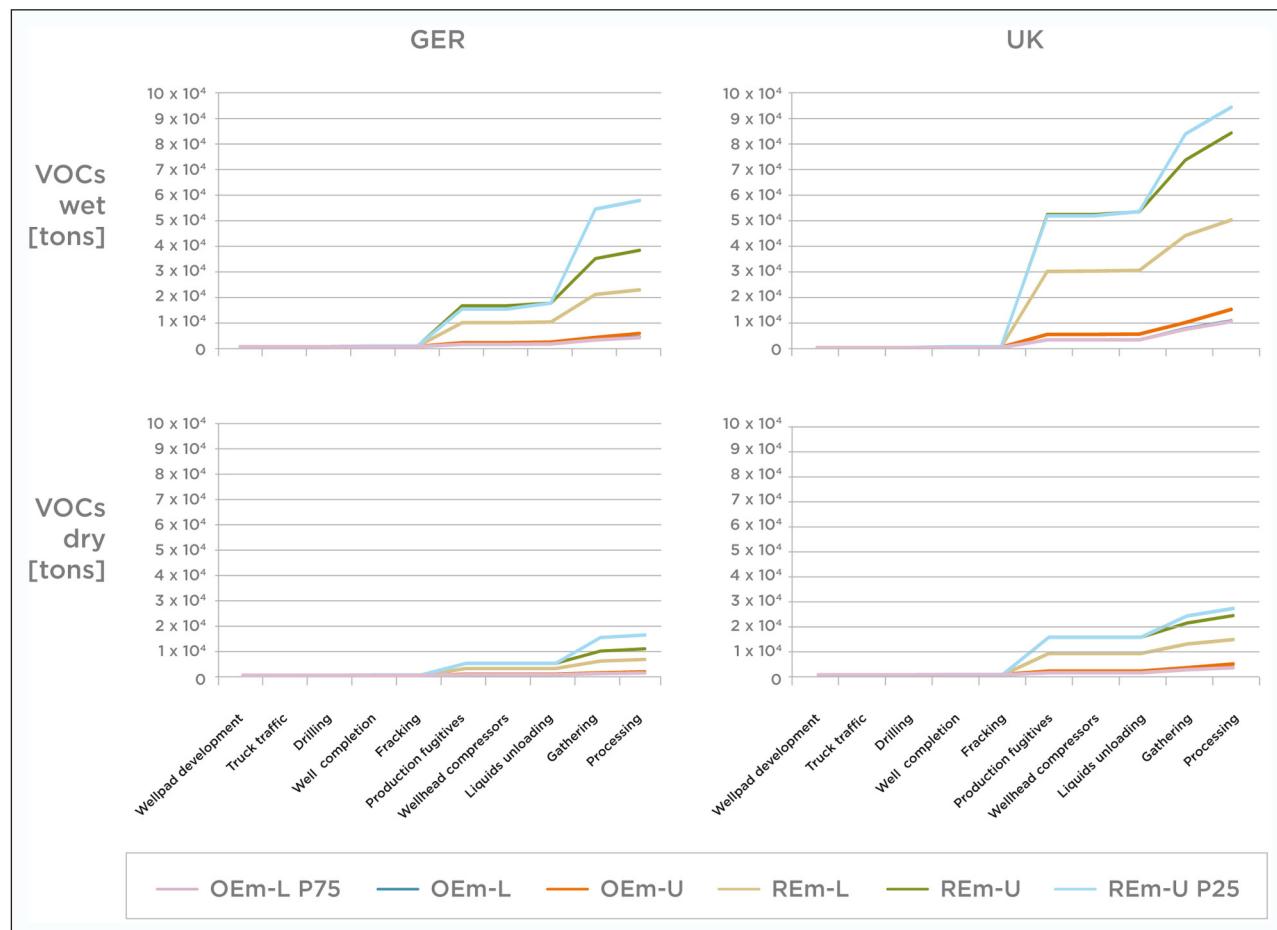


Figure 11: Cumulative annual emissions along the shale gas production chain. Results for Germany (left) and the UK (right) in tons. OEM and OEM are shown for the P50 case, while OEM-U P25 and OEM-L P75 are also reported to show the emission boundaries. DOI: <https://doi.org/10.1525/elementa.359.f11>

VOC emissions in both Germany and the UK have been decreasing over the past few decades (EEA, 2016). As reported in **Table 5**, total VOC emissions emitted by the energy sector were 83 Kt for Germany and 129 Kt in the UK for the year 2016 (NAEI, 2018; UBA, 2018c). This means that our results are equivalent to 4.5 to 46.2% of total annual VOCs emissions from the German energy system, and 8.3 to 66.5% for the UK (for all scenarios, including wet and dry). Nevertheless, it is worth emphasizing here the dominant role that VOC concentration in the natural gas can play when estimating total VOCs outputs. The sectors which are the most consequential for VOC leakage in shale gas production are the same as for CH₄, being these two compounds co-emitted, i.e., production, gathering and processing. These sectors vary in level of contribution depending on the country and scenario. For example, gathering is by far the most crucial sector for VOC emissions in Germany under the OEM-U P25 scenario. This is mostly due to the low productivity of German basins, which requires a greater number of wells to be drilled and in turn a greater number of gathering facilities and associated emissions. Based on these values, the VOCs emissions in these scenarios have the potential to notably impact local and regional air quality through O₃ production.

Nitrogen oxides (NO_x)

NO_x are exhaust by-product emitted by engines during combustion of fuels and a precursor to O₃ which negatively impacts human and environmental health. In our emission scenarios, NO_x are mostly produced during fracking, at gathering plants and during gas processing due to the extensive employment of diesel engines at these stages (**Figure 6**).

In the P50 scenarios, NO_x emissions range between 2.2 and 7.4 Kt in Germany and between 3.7 and 14.9 Kt in the UK. NO_x under P75 conditions display lower emissions by ca. 25% in Germany with respect to the lowest level reported under P50. Similarly, a lower value of about 25% is evidenced under P25 conditions with respect to the highest emissions under P50. In the UK, under P25 and P75 smaller variances are shown with respect to the

P50 range boundaries, demonstrating a weaker dependence of emissions on well productivity. Our results show that the number of fracking stages necessary to exploit the shale reservoir under each well pad is mainly responsible for NO_x emissions at the well site, and a lower number of those can reduce emissions by up to a factor of five. Nevertheless, it is worth pointing out that the number of fracking stages is strictly dependent on the local geological characteristics of the reservoir which are unknown up until the drilling phase starts and cannot be controlled. Emission reductions systems employed in REm are particularly efficient at gathering stations, where the number of facilities is the main factor responsible for curbing NO_x release with respect to emission factors of engines or electricity-driven motors. During processing, high efficiency combustion (>50%) and high-performing water-steam injection gas turbines employed in OEM can together cut NO_x emissions up to 80%.

NO_x emitted from our scenarios account for only a small fraction of the national emissions associated with the energy sector. In both countries examined, NO_x emissions show a slow but constant decrease since the 1980s, with a parallel decrease in atmospheric concentrations (Minkos et al., 2018; NAEI, 2018). These trends follow more stringent regulations especially in the transport sector, which is the greatest contributor to total NO_x emissions. Energy production systems released 260 Kt of NO_x in Germany and 125 Kt in the UK in 2016, so that a potential shale gas industry as envisaged in this study does not have a significant impact on national inventories or on background levels (contributing 0.8/2.8% in Germany and 3/12% in the UK). A complete overview of NO_x national emissions and results from our study is reported in **Table 5**. Nevertheless, clustering of large emitters such as new well sites, gathering or processing plants may severely increase NO_x concentrations nearby so that it might have a considerable impact on air quality e.g., O₃ production, calling for smart industrial planning and appropriate prevention measures for these facilities. Gas flaring is also another important source of NO_x, and atmospheric concentration of these species can be significantly affected by this activity

Table 5: Annual air pollutant emissions from this study compared with national databases. All values are reported in Kt. The energy system includes public electricity and heating generation. ¹UBA (2018c); ²NAEI (2018); ³NAEI (2018) (stationary combustion sector); ⁴Minkos et al. (2018); ⁵UBA (2018a); ⁶UBA (2018b). DOI: <https://doi.org/10.1525/elementa.359.t5>

Pollutant species	Emissions, this study (shale gas industry, P50 case)				National emissions (total)		National emissions (energy system)	
	GER		UK		GER [Kt]	UK [Kt]	GER [Kt]	UK [Kt]
	OEm [Kt]	REm [Kt]	OEm [Kt]	REm [Kt]				
VOCs	Wet	3.8–5.3	22.7–38.5	10.7–15.3	51.0–85.8	1,050 ¹	821 ²	83 ³
	Dry	1.0–1.5	6.3–10.6	2.9–4.2	14.1–23.6			
NO _x		2.2–3.3	5.3–7.4	3.7–5.3	10.9–14.9	1,220 ⁴	893 ²	260 ²
PM ₁₀		0.1–0.2	0.3–0.4	0.4–0.5	0.7–0.9	203 ⁵	170 ²	11 ⁵
CO		0.3	0.8–1.0	0.6–0.8	2.2–2.9	2,840 ⁶	1,490 ²	418 ³

(Duncan et al., 2015; Li et al., 2016). We did not attribute any emissions to flaring activities in our shale gas production system (with only a few exceptions, i.e., safety), although some of the top-down source studies selected to assign emissions may include this in their aggregate results. Our choice to exclude flaring in future scenarios is in accordance with worldwide initiatives such as the "Zero Routine Flaring by 2030" by the World Bank, and because of this CH_4 emissions presented here may lack a relevant source when comparing them to real case-studies.

Particulate matter (PM)

PM is an air pollutant which has negative implications for health and climate change. These particles are generated by several natural processes, while the industrial and transport sectors are the dominant anthropogenic sources (AQEG, 2012). In Germany, total annual PM_{10} emissions from the power and heat industry in 2016 registered at 11.1 Kt (UBA, 2018a), and 3.3 Kt in the UK (NAEI, 2018). An overview on PM₁₀ emissions is reported in **Table 5**. The lower amount of coal usage in the UK energy mix may be responsible for the notable difference in PM emissions from this sector between the two countries: 8.5 Mtoe in the UK vs. 39.3 Mtoe in Germany (BMWi, 2018; GOV.UK, 2019). PM_{10} and $\text{PM}_{2.5}$ emissions are nearly identical in our study, because the majority of PM released by diesel engines and turbines are within the $\text{PM}_{2.5}$ range, which by definition is also within the PM_{10} range. Therefore, from now on we refer to PM_{10} only.

In our emission scenarios, PM_{10} is produced by diesel engines (locally) and indirectly by electricity consumption from machineries at all stages. As shown in **Figure 6**, PM_{10} emissions in the P50 scenarios fall within the range of 0.2–0.4 Kt (REm) and 0.1–0.2 Kt (OEm) in Germany, and 0.6–0.9 Kt (REm) and 0.4–0.5 Kt (OEm) in the UK. Results from the P25 and P75 scenarios do not show remarkable differences beyond this range. Although these values contribute less than 3.6% of total PM emitted by the German energy sector, in the UK they contribute up to 27%. Addressing their potential health and environmental implications identifying best shale gas production practices is therefore required. PM_{10} emissions are mainly produced during the gas processing stage (>70% of total volumes), and to a minor extent during drilling, fracking and gathering operations (in order of importance). PM_{10} emitted by the intensive truck movements from gas exhaust, tires, brakes and road wear affect total emissions only minimally, though they may have significant effects at the local level. High turbines efficiency at processing plants applied in OEm ameliorates PM_{10} emissions to a minor extent. Although drilling does not have a considerable impact on total emissions, it is worth noting that substitution of diesel engines with electrical motors powered by the electrical grid power has the potential to reduce emissions by a factor of 16 from this stage, which may signal significant implications for air quality at well sites. Any reduction of diesel engines usage at any stage of the production chain is linearly related to the decrease of total PM_{10} emissions. An overview or results is presented in **Table 5**.

Carbon Monoxide (CO)

CO is an odorless and colorless air pollutant produced by natural as well as anthropogenic processes (Khalil and Rasmussen, 1990; Guenther et al., 2000). CO emissions from all sectors in the UK have been steadily decreasing since 1990 (NAEI, 2018), and in the last years over half of its emissions are attributed to residential sector combustion (414 Kt in 2016) and stationary combustion (418 Kt, 28% of total emissions; NAEI, 2018). In Germany, total CO released in 2016 decreased by more than 70% compared with values reported in 1990, with the energy sector currently responsible for 148 Kt (5.2% of the total) (UBA, 2018b). All CO national emissions and our results are reported in **Table 5**.

Our results show that CO, likewise to NO_x and CO_2 , is only emitted at production stages where engines, turbines or motors burning diesel or natural gas are employed. We assume that no CO is present in the shale gas based on the speciation we apply from Faramawy et al. (2016). Accordingly, the processing stage dominates CO emissions in Germany accounting for more than 50% in OEm and more than 80% in OEm, followed by gathering stage which accounts for less than 25% of CO released in all scenarios. These shares are more extreme in the UK, where processing accounts for more than 90% of total CO emissions in REm and almost 80% in the REm (see **Figure 6**). The large volume of gas combusted to provide power and in turn process the shale gas is therefore responsible for most of the CO released by the gas production industry. CO volumes as calculated in REm (between 2.2 and 2.9 Kt for the UK and between 0.8 and 1.0 Kt in Germany) and in OEm (between 0.6 and 0.8 Kt for the UK and 0.3 Kt for Germany) are considerably lower than values currently attributed to the power and heat production sectors in both countries (see above).

Conclusions

In this study we investigated: i) several development pathways of an upstream shale gas industry in Germany and the UK; ii) the GHG and air pollutant emissions resulting from these different pathways; and iii) the potential of different practice performances and technological solutions to control losses and ensure best climate standards. Based on shale gas reservoir estimates in these two countries, an industrial development that is able to maintain current gas production volumes for the next decades is within reach. Accordingly, our drilling projections show that a constant annual drilling rate of 480 wells in the two countries can lead to a flourishing and mature shale gas industry in one to eight years. Our investigation into the climate and atmospheric repercussions associated with such an industry quantifies emissions in the shale gas basin regions under business-as-usual (REm) and best-technical-case (OEm) frameworks, with the latter representing the minimum emissions achievable according to the technical boundaries. Well productivity, which cannot currently be predicted, has proven to be an important factor in the total emissions released. Although it is not possible to influence this variable through activity performance

and regulations, by considering all well productivities we have a complete overview of the extreme boundaries of our emission projections. Based on the drilling scenarios, the amount of shale gas produced annually is 11.58 bcm in Germany and 36.62 bcm in the UK. Between the scenarios, there is a wide emission variation between GHGs and air pollutants, with the OEM comparable to estimates reported in European national inventories. Although hypothetically feasible, it is very unlikely that all the conditions assumed in the optimistic scenario will be systematically met, i.e., application of best regulations, strict emission standards, best engine technology/performance, and lowest gas leakage estimates across all stages of the production chain. GHGs released under REm P50 scenarios range from 46.4 to 175.3 Kt for CH₄ (equivalent to 10.3 and 65%, respectively, of the total emissions from the current heat and power sector in the reference country) and between 1.8 and 4.9 Mt for CO₂ (equivalent to 0.5 and 3.5% of current total country emissions). Figures generated by OEM are significantly lower, ranging from 1.6 to 11.6% (CH₄) and from 0.9 to 2.0% (CO₂) of total country emissions. The CH₄ contribution to total CO₂-eq. emissions generated by our shale gas industry is ca. 25% in OEM (min) compared to ≥50% in all other cases (see **Figure 7**), indicating the climate effectiveness of measures aiming at curbing CH₄ emissions. In the broader carbon footprint perspective, our results depict scenarios where the shale gas EI for electricity generation is systematically higher than estimates of the current EI for gas in Germany, ranging from +3 to +35% when considering all well productivity and performance/technology cases. Conversely, the same results are below or similar to the CF assigned to the national power grid, and one half and one third of the EI indicated for hard coal and lignite, respectively.

CH₄ leakage in the shale gas upstream sector as a percentage of total gas production in REm ranges from 0.38 to 0.90% under the P50 case, and between 0.35 and 1.36% overall. Losses are much more constrained in OEM and range between 0.08 and 0.13% in the P50 case, and between 0.08 and 0.15% when the P25 and the P75 cases are considered. The emissions generated in OEM are comparable to official governmental figures in national inventories. On the other hand, CH₄ leakage rates reported in several field studies carried out in the US and elsewhere show leakage rates similar or slightly higher than those evidenced in REm: between 0.9 and 1.9%. The reason for the discrepancies between official estimates in Germany and the UK, and emissions reported by studies from the US are not fully understood, and may be caused by under-reporting of current emissions or by substantial differences in gas production practices, CH₄ monitoring, and maintenance of facilities and equipment. Further investigation in this direction is necessary.

The release of air pollutants along the entire shale gas production chain represents a significant health threat. Limiting our analysis to the P50 production case, we estimate that the release of CO, NO_x and PM₁₀ to the atmosphere may be negligible in all scenarios when compared to national emissions. On the other hand, VOC losses can

be relevant in REm, and strategies to abate them are applicable and explored in OEM. Air pollutants, as opposed to GHGs, have direct health repercussions at the local and regional levels. Our scenarios only focused on total annual emissions, while investigations of their implications for local and regional air quality are addressed in a follow-up study through the application of atmospheric chemistry modeling. The large variability of emissions of all air and climate pollutants described by REm and OEM testifies to the value and potential of implementing existing best technologies/practices across the different gas production stages. Based on the latest engineering innovations in this field and recent scientific findings, emissions can be ameliorated by a rigid and accurate regulatory scheme, keeping in mind that results under OEM are based on technically feasible emission reduction measures and technologies that are rather unlikely to be systematically employed or achieved. Our results suggest that this is the only chance for gas to represent a transitory solution when carbon-free technologies cannot be deployed. The development of new natural gas systems that are regulated by outdated or inappropriate legislation is – as largely proved by the existing literature – a missed opportunity. The same is true for existing gas systems, where other studies have shown how technical CH₄ leakage reduction strategies are mostly easy to implement and are likewise cost effective, especially when the gas price is high (ICF 2015, 2014). In light of this and conscious of the climate crisis that the planet is currently facing as emphasized in the latest IPCC report released in 2018, addressing gas environmental hazards needs to swiftly take center stage in government policies and in negotiations with gas operators. Our findings on the potential risks of a future European shale gas industry also call for full environmental compliance to minimize inevitable shortcomings in the event that shale gas becomes a reality in Europe.

Data Accessibility Statement

The authors have no data accessibility statement to declare.

Notes

¹ Available at: <http://www.sciencemag.org/news/2018/06/natural-gas-could-warm-planet-much-coal-short-term>. Accessed 15 April 2019.

² Available at: <https://www.dieselnet.com/standards/eu/nonroad.php#s3>. Accessed 15 April 2019.

³ Based on natural gas conversion standards provided by the International Gas Union (IGU).

Supplemental files

The supporting information describes how the drilling projections are constructed, the technical aspects of the O&G industry that are discussed, and the reservoir productivity cases (SM Text S1, Section S1). Activity data, emission factors and their application to each stage of the shale gas supply chain under different technology and productivity scenarios is provided in SM Text S1, Section S2. The sensitivity analysis of the emission scenarios is presented in the remaining SM Text S1, Section S3.

The supplemental files for this article can be found as follows:

- **Text S1.** Supplemental text. DOI: <https://doi.org/10.1525/elementa.359.s1>

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Substantially contributed to conception and design: LC, LBW, TB
- Contributed to acquisition of data: LC, LBW
- Contributed to analysis and interpretation of data: LC, LBW, TB
- Drafted and/or revised the article: LC, LBW, TB, HDVdg, MPB
- Approved the submitted version for publication: LC, LBW

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