The quantification of methane emissions and assessment of emissions data for the world's largest gas supply chains

Jasmin Cooper[a,b], Paul Balcombe[c], Adam Hawkes[a,b]*

[a]Sustainable Gas Institute, Imperial College London, SW7 1NA, London, UK
[b]Department of Chemical Engineering, Imperial College London, London, SW7 2AZ, UK
[c]Division of Chemical Engineering and Renewable Energy, School of Engineering and Material Science, Queen Mary University of London, London, E1 4NS, UK
*Corresponding author at: Sustainable Gas Institute, Imperial College London, London, SW7 1NA, UK. Tel.: +044-020-759-47406. Email address: jasmin.cooper@imperial.ac.uk

Abstract
Methane emitted from gas supply chains are a major source of greenhouse gas emissions, but there is uncertainty on the magnitude of emissions, how they vary, and which key factors influence emissions. This study estimates the variation in emissions across the major natural gas supply chains, alongside an estimate of uncertainty which helps identify the areas at the greatest emissions 'risk'. Based on the data, we estimate that 26.4 Mt CH_4 (14.5-48.2 Mt CH_4) was emitted by these supply chains in 2017. The risk assessment identified a significant proportion of countries to be at high risk of high emissions. However, there is a large dependency on Tier 1 emission factors, inferring a high degree of uncertainty and a risk of inaccurate emission accounting. When emissions are recalculated omitting Tier 1 data, emissions reduce by 47% to 3.8-fold, downstream and upstream respectively, across regions. More efforts in collecting robust and transparent primary data should be made, particularly in Non-Annex 1 countries, to improve our understanding of methane emissions.

Keywords: methane emissions, emissions intensity, natural gas supply chains, emissions data

1. Introduction

The accurate quantification of methane emissions is an increasingly important topic as climate targets become more stringent. Methane is the second most critical greenhouse gas (GHG), and is estimated to have caused 25% of anthropogenic global warming seen today (EDF, 2019). It is a potent GHG, having a global warming potential (GWP) 28-34 times that of CO_2 over a 100-year timeframe, and 84-87 times that over 20 years (Balcombe et al., 2018b, Myhre et al., 2013). The atmospheric concentration has been rising and over the past decade approximately 13 Mt/yr has been added to the atmosphere (Saunois et al., 2020). Whilst the overall balance of sources and sinks (emissions and oxidation into CO_2, respectively (Saunois et al., 2020)) is well understood, the contribution from the various emission sources carries very high uncertainties. Emissions from natural gas are highly variable across regions, supply chain stages and users (Balcombe et al., 2018a). This combined with the size and nature of methane emissions from natural gas production, transport and use, makes them more difficult to accurately estimate.

Recently, countries have pledged to be net-zero by 2050/60 and a number of these have implemented methane strategies in order to curb their emissions of this potent GHG (Hausfather, 2020, European Commission, 2020). In the oil and gas sector, there have been many efforts put into quantifying methane (EDF, 2020, GMI, 2020, Lammey, 2020, Nowlan, 2017, OGCI, 2018b, Xu et al., 2020). However, many regions in the world lack in the knowledge and capabilities to quantify their methane emissions through direct measurement methods (IEA, 2021) and consequentially, many rely on de facto emission factors to estimate their emissions.

In the oil and gas methane emissions literature, at the time of writing, there have been many studies conducted to measure emissions from emission sources e.g. abandoned wells, facilities, basins (Allen et al., 2013, Alvarez et al., 2018, Caulton et al., 2014, Conley et al., 2016, Cui et al., 2017, Cui et al., 2015, Fox et al., 2019, Kang et al., 2014, Kort et al., 2014, Marchese et al., 2015, Oonk and Vosbeek, 1995, Ravikumar et al., 2018, Ravikumar et al., 2019, Schneising et al., 2014, Zhang et al., 2020). However, there has been limited efforts put into quantifying emission across whole supply chains and determining how emissions vary by supply chain e.g., what is the emissions difference between pipeline or LNG imports from the same country and does country of gas origin impact emissions? As far as the authors are aware, only the IEA and thinkstep have conducted studies to estimate methane emissions across supply chains (IEA, 2020, thinkstep, 2017), but these have either considered emissions within country boundaries, or estimated emissions for a small number of supply chains. Also, as far as the authors are aware, no studies have attempted to assess the reliability or accuracy of the emission data used in national GHG inventories. Therefore, there is currently a gap in the knowledge on how emissions vary across whole supply chains, as well as how uncertain the current emissions data is. The latter is of particular importance as studies which have compared emissions estimated via independent measurement campaigns to emissions reported in national GHG inventories have found that national inventories may be underreporting emissions by as much as 60% across the whole gas value chain (Alvarez et al., 2018).

This study aims to estimate the methane emissions and emissions intensity for the world's largest gas supply chains, as well as assess the reliability of the underlying emissions data. The work presented in this paper aims to answer:

- How much methane is emitted by the largest gas supply chains and how do they vary?
- What is the emissions intensity across these supply chains and how do they vary?
- What is the reliability of the underlying emissions data and hence how accurate are the emissions reported in national GHG emission inventories?

The outputs of this study may be used to identify key emission reduction requirements for industry and policymakers, as well as highlighting key areas where better emissions data is urgently required and aiding in the development of emissions inventories, such as the European Union Methane Strategy's Methane Supply Index (which aims to put pressure on gas producers to reduce their emissions) (European Commission, 2020).

2. Methodology

In this work, we estimate the methane emissions (kt CH_4 and emissions intensity) for the largest gas supply chains, as well as conduct an uncertainty analysis and a risk assessment of the underlying emissions data. The methane emissions calculated are based on emission factors and gas throughputs reported in the literature. Emissions in kt CH_4 are estimated by multiplying the emission factor by the gas throughput, while the emissions intensity is calculated by dividing the emissions by the total gas throughput of the supply chain. The uncertainty in emissions is estimated through bootstrapping resampling (Section 2.4.1). A risk matrix has been developed to identify regions at risk of high emission (Section 2.4.2). Emission factor data, gas throughput, the uncertainty analysis and risk assessment are described in more detail further on in this section. For further details on how methane emissions are calculated, please refer to IPCC (2006).

The 17 countries which make up the world's largest gas producers and consumers are the focus, and countries which import/export gas to these countries are also considered. These 17 countries were selected based on their total gas production and consumption, while also accounting for the majority of global gas production, consumption and trade. The countries selected represent the largest gas producers, consumers, gas (pipeline and LNG) importers and exporters in 2017. Including the countries which import/export gas to and from these countries, a total of 80 countries and 252 supply chains are considered, accounting for: 65% of consumption and LNG trade, 72% production and 77% pipeline trade.

2.1. Estimating emissions and risk

The approach to estimate emissions and risks are illustrated in Figure 1. The emissions data are primarily collected from data reported in national GHG inventories submitted to the United Nations Framework Convention on Climate change (UNFCCC) under the Kyoto Protocol (UNFCCC, 2020b). These were used in combination with gas production, consumption and trade data, to estimate emissions from the world's largest gas producers and consumers. All supply chains are considered: domestic production, exports (pipeline and liquefied natural gas (LNG)), imports (pipeline and LNG) and domestic consumption, as shown in Figure 2. Data from 2017 is used as at the time of writing, it is the most recent inventory submitted to the UNFCCC (UNFCCC, 2019b, UNFCCC, 2019a).

Emission factor data and their associated uncertainties, gas throughput and gas loss were collected. As emission factor data for 2017 is used in this study, gas production, consumption and import/export volumes in 2017 were used to estimate total emissions and emission intensities. The supply chain stages are combined by incorporating estimates of natural gas losses across the supply chain, to derive a total estimate of emission intensities per unit of gas produced or delivered. The associated uncertainties are then used to estimate the higher and lower bounds of this estimate. An uncertainty analysis of the emissions data was then conducted through bootstrapping resampling, and a risk assessment carried out to estimate the risk of high emissions. Each of these data types and their sources are described in more detail below.

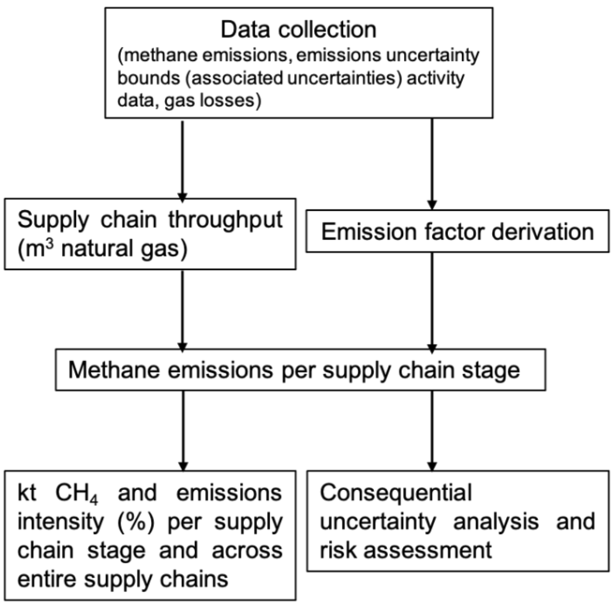

Figure 1: Steps followed to develop emissions model. Emissions model allows total methane and emission rate to be compared for various supply chains. Kilotonne: kt.

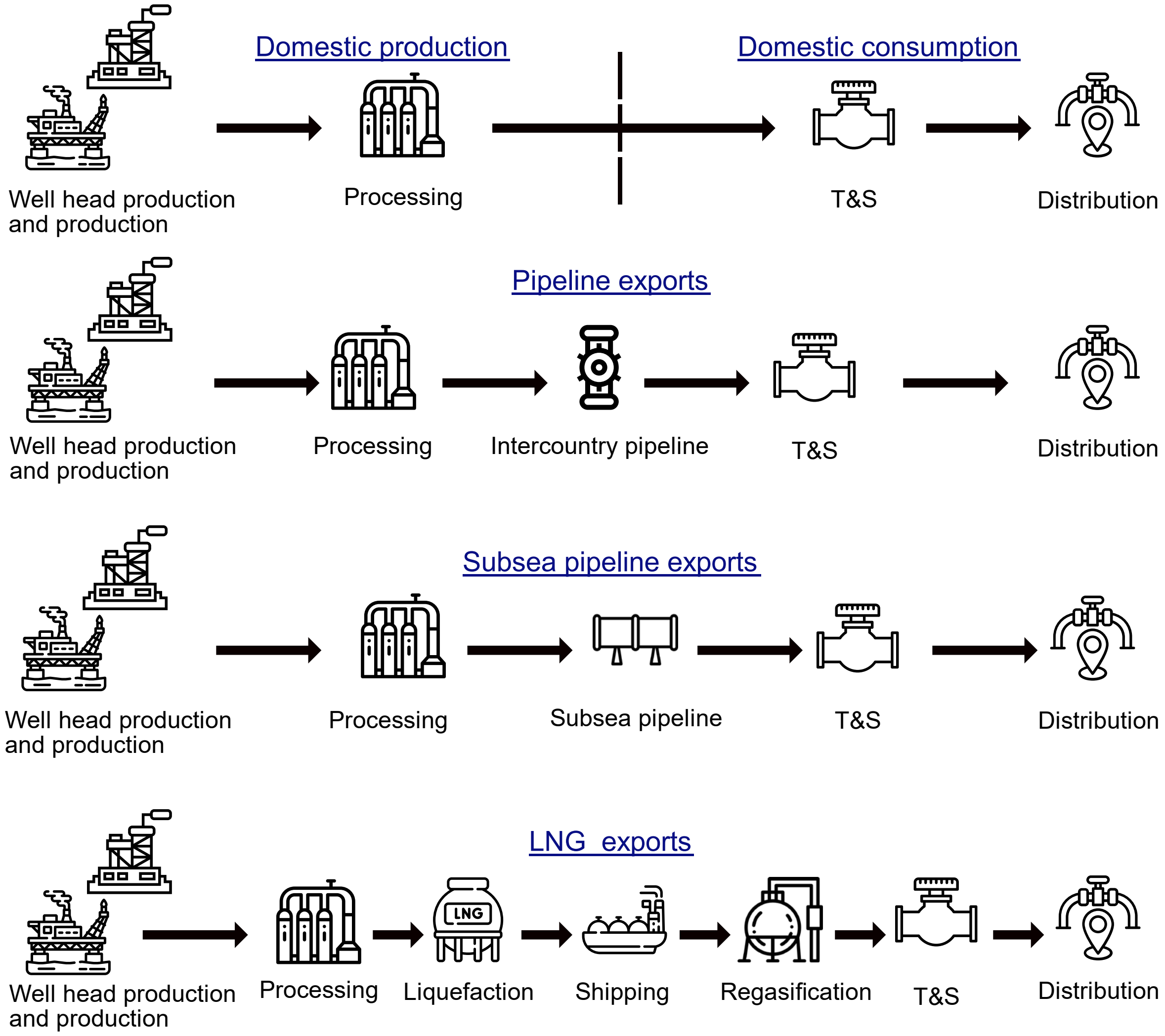

Figure 2: Supply chains considered. Upstream considers gas production and processing while midstream considers gas trade and downstream considers transmission and storage (T&S) and distribution.

2.2. Supply chain throughputs: production, consumption and trade data

The gas throughput is the volume of gas passing through a supply chain or supply chain stage and is also referred to as the activity data. Data on gas production, consumption and trade were collected from open-source literature. The BP World Energy Outlook (BP, 2019) and International Gas Union (IGU) annual report (IGU, 2018) were the primary sources and government energy statistics reports were used to fill in any gaps. The throughput is not constant throughout a supply chain. Gas losses (Section 2.2.1) occur when gas is used as a fuel within a stage e.g., compressor stations, gas processing, ship fuel. A summary of throughputs is given in Table 1.

Table 1: Supply chain throughputs- gas production, consumption and trade in billion cubic meters (bcm) (UNFCCC, 2020a, UNFCCC, 2020b, UNFCCC, 2019b, IGU, 2018, Gazprom, 2018, BP, 2019).[a,b]

Country	Production	Consumption	Imports	Exports
USA	745.8	739.4	80.7 (P,1)	66.1 (P,2)

Russia	635.6	454.5	2.1 (L,2) 18.9 (P,2)	17.4 (L,25) 215.4 (P,33) 31.0 (L,6)
Iran	223.9	214.4	1.7 (P,1)	12.5 (P,4)
China	149.2	240.4	39.4 (P,4) 52.6 (L,18)	-
Canada	177.6	109.7	24.0 (P,1) 0.4 (L,3)	80.7 (P,1)
Qatar	175.7	47.4	-	18.4 (P,2) 103.4 (L,25)
Australia	112.8	41.2	5.8 (P,1)	75.9 (L,9)
Norway	123.2	4.6	-	109.2 (P,9) 4.8 (L,17)
Malaysia	78.4	42.8	0.7 (P,1) 2.0 (L,2)	1.5 (P,1) 36.1 (L,10)
UK	41.9	78.8	39.4 (P,2) 7.1 (L,9)	10.8 (P,3)
Japan	3.0	117.0	113.9 (L,18)	-
Egypt	49.0	56.0	9.5 (L,9)	1.2 (L,8)
Germany	6.4	90.2	94.8 (P,4)	-
Argentina	37.1	48.5	6.6 (P,2) 4.8 (L,8)	-
Italy	5.3	72.1	53.8 (P,5) 8.4 (L,7)	-
Netherlands	38.6	36.1	40.9 (P,4) 2.7 (L,6)	43.3 (P,5)
Bolivia	17.1	2.2	-	14.9 (P,2)

[a](X,Y); X is import/export type and Y is number of supply chains of type X
[b]P-pipeline import/export; L-LNG import/export

2.2.1. Gas losses

Natural gas is typically used as a fuel for processes along the supply chain and this use is known as the gas loss. This is an important consideration so that the methane intensities along the whole supply chain can be aggregated, to estimate an emission per unit of produced or delivered gas. The following literature was used to source this data (refer to Section 1 in the Supporting Information (SI) for gas losses used in this work):

- thinkstep gas losses for production, processing, T&S and distribution (thinkstep, 2017);
- Exergia for gas losses in production, processing, T&S and distribution (Exergia, 2015); and
- thinkstep gas losses for LNG liquefaction, shipping and regasification (thinkstep, 2017).

2.3. Emission factors- data sources, disparity within the data and using the data to estimate emissions

Emission factors are emission rates of a given process or activity. Emission factor data reported in submissions to the UNFCCC were primarily used to estimate emissions. The data collected and used in this work can be found in the SI. While some of the countries considered have independently derived emission factors, the majority do not. Consequently, the UNFCCC data is the only source of data for many countries. Where this data was not available e.g. gas transport in pipeline and LNG carriers, the following data sources were used:

- thinkstep emission factors for production and processing (thinkstep, 2017);
- Marcogaz emission factors for pipeline trade (MARCOGAZ, 2017, MARCOGAZ, 2018);
- thinkstep gas losses and emission factors for LNG (thinkstep, 2017); and
- Tokyo Gas for regasification gas loss and emission factor (Tokyo Gas, 2018).

Emission factors fall into one of three tiers, as classified by the Intergovernmental Panel on Climate Change (IPCC) based on the methodology used to quantify emissions (IPCC, 2006):

- Tier 1- generic emission factors for developed and developing/transitioning economies;
- Tier 2- region specific or country specific depending on data availability; and
- Tier 3- country specific determined by experts from primary data.

The accuracy of estimates varies across the tiers. However, even within these broad tiers there exist large variations in measurement methods and consequently uncertainties. Tier 2 and 3 emission factors are derived from sample measurements, but the quality and representativeness of the sample is not stipulated within the guidance. Additionally, emission factors should be updated regularly, but this is not considered within the tier allocations. Thus, the reporting and transparency of emission factors varies across regions and consequently the following assumptions were made:

- countries which developed Tier 2 or Tier 3 emission factors but were not disclosed, Tier 1 emission factors were assumed. Specifically: Qatar, the United Arab Emirates and China;
- countries which have not submitted to the UNFCCC, Tier 1 emission factors were assumed. Specifically: Libya;
- countries which have not submitted to the UNFCCC recently, but alternative data are available. Specifically: Algeria;
- countries which have submitted to the UNFCCC, but more recent data is available. Specifically: Trinidad and Tobago;
- LNG liquefaction and regasification emission factors were taken from thinkstep (thinkstep, 2017) and considered as separate stages. Most submissions did not describe in detail whether emissions from liquefaction or regasification are included in 1b2b- '*emissions from venting, flaring and fugitive sources from natural gas production, transmission and distribution*.' As emissions from these stages are reported in the literature to be much lower than in the upstream and downstream stages (thinkstep, 2017), see Section 3.1 for more details, the impact of double counting was not considered to have a significant impact on the overall results;
- the shortest LNG shipping distance (SEA-DISTANCES.ORG, 2019) was assumed, due to natural gas being a high demand commodity and boil-off increasing with journey time;
- intercountry pipeline distances were estimated based on the European Network of Transmission System Operators for Gas (ENTSOG) map for European gas trade and

Google Earth (based on 'as the crow flies' distance between country borders) for non-European countries;

- T&S emission factor of export country is used for pipeline exports between countries which share a border;
- gas exports/imports listed as 'Other' or 'Re-exports' were assumed to go to or originate from the largest market in the region; and
- for stages which do not have an IPCC emission factor category (subsea and intercountry pipeline, liquefaction, LNG shipping and regasification), uncertainty of ±100% is applied, based on the review of the uncertainty methodologies in UNFCCC submissions (IPCC, 2006, UNFCCC, 2020a, UNFCCC, 2020b, UNFCCC, 2020c).

A detailed breakdown of the data collected is given in the SI. Emission factor data was collected for each supply chain stage (Figure 2). This was done by reviewing the GHG emission inventories submitted to the UNFCCC for all 80 countries. The emissions were calculated in cubic meters (m^3) of CH_4 by multiplying the emission rate by the throughput of each stage. The emission intensity calculated by dividing the m^3 emissions by either the volume of gas produced or consumed; throughput in wellhead production or distribution, respectively. The emissions from each stage can then be summed to calculate the emissions across the whole supply chain. It should be noted that emission data are scarce in the literature. At the time of writing, the reports by thinkstep, Marcogaz and Exergia and the information provided by Tokyo Gas are the only alternative open access sources available.

2.4. Consequential uncertainty in emission estimates and risk of high emissions

2.4.1. Uncertainty assessment of the emissions data via bootstrapping resampling

The emissions data collected have variable uncertainty associated with it, which we consider. Tier 1 emission factors are conservative as they are generic to multiple countries and these are typically larger than Tier 2/3 emission factors. As a mixture of emission factors are used, the impact of the Tier 1 data is assessed through bootstrapping resampling. This is a random resampling method which generates a new dataset by resampling the original dataset with replacement. This method was used over other resampling methods as the original dataset (IPCC emission factor data collected for the production, processing, T&S and distribution stages for all 252 supply chains) is substantial.

In MATLAB, bootstrapping resampling was run with the original dataset as is and omitting Tier 1 emission factors. In total, 400 new datasets were generated. The emissions for each supply chain were then recalculated using these new datasets and compared with the original estimate. The mean and variation in emission factors were also compared between the original and resampled datasets. Significant differences between the original and resampled datasets, as well as between the original and recalculated emissions, would indicate a high level of uncertainty in the emission factor data.

2.4.2. Risk assessment to estimate the 'risk' of high emissions

A risk-based approach to estimate the 'risk of high emissions' for each region, was carried out for the supply chain stages: production, processing, T&S and distribution. Risk is the product of a consequence and the likelihood of occurrence. In this case, consequence is the emissions intensity, as estimated following the methods outlined in Sections 2.1 to 2.3. This can range from minor to extreme depending on how it compares to a benchmark emission intensity. As many oil and gas companies have set methane intensity targets, we have chosen to use the Oil and Gas Climate Initiative (OGCI) target of 0.2% as the benchmark. This is a collective target applicable to 32% of global oil and gas production (OGCI, 2018a). The likelihood refers to the accuracy in estimated emissions, which is estimated based on the IPCC tier. Tier 1 is assigned very high likelihood of inaccurate emissions and Tier 3 low likelihood. The consequence multiplied by the likelihood will give an estimate of the risk of high emissions. See Section 3 in the SI for more details, including the risk matrix developed.

3. Results and discussion

An assessment of emission factors is presented first, followed by the estimated emissions and emission intensities of the supply chains. The emissions estimated in this work is compared with literature values (IEA Methane Tracker). The consequential emission factor uncertainty, assessed through bootstrapping resampling is then presented, along with the results of the risk assessment. The emissions results of each supply chain will not be discussed in detail due to the large number. The individual country and supply chain emission results can be found in the SI.

3.1. Emissions factors- IPCC tier and emission factors per supply chain stage

The majority (72%) of the IPCC emission factor data collected for this work are Tier 1 (Figure S1 in the SI). These are typically used by Non-Annex-1 countries (developing countries, under the Kyoto Protocol) in the absence of primary data. Please note that this is the categorisation used by the UNFCCC to distinguish between Party types to the Convention and hence has been used in this work. Annex-1 countries (industrialised countries and a selection of economies in transition) also use Tier 1 emission factors as placeholder data, where primary data is unavailable. Tier 3 and 2 emission factors are applied mostly by Annex-1 countries. This could be because of the high cost (financial, time and human resources) associated with measuring and reporting emissions. However, when comparing tiers, Tier 1 emission factors can be up to 6.6-times higher than Tier 2 and 3. In addition, the uncertainty bounds associated are much higher; ±20% to ±500% uncertainty for Tier 1 while Tier 2 and 3 have uncertainty bounds of ±5.2% to ±276% (IPCC, 2003, IPCC, 2006, UNFCCC, 2019b). The uncertainty bounds associated with the Tier 1 data is much higher as the data is generic. For the Tier 2 and 3 data, statistical methods are used to estimate errors, either propagation of errors or Monte Carlo Simulation. The errors estimated vary depending on both the method used to estimate uncertainty, as well as the data used to estimate emissions, which resulted in a large (but smaller than Tier 1 data) variation in uncertainty bounds.

There is a large variation in emission factors for the different supply chain stages. The production stage has the highest emission factor by far, followed by distribution and T&S (Figure 3). One reason for why production has a much higher emission factor could be because a mixture of Tier 1 and 3 emission factors are used to estimate emissions (see the SI for more details). A large number of gas producing countries are Non-Annex-1 while Annex-1 countries make up a large proportion of gas consuming countries. Consequentially, the higher usage of Tier 1 emission factors could have resulted in production having higher emissions. Gas trade has the lowest emission factors, but it should be noted here that the methane emission data on the transport of gas is not robust, in particular relating to LNG transport (Speirs et al., 2019). Gas transported through pipelines has a similar emission factor to LNG shipping. However, as liquefaction and regasification are necessary for LNG trade, its overall emission factor is higher than in pipeline trade.

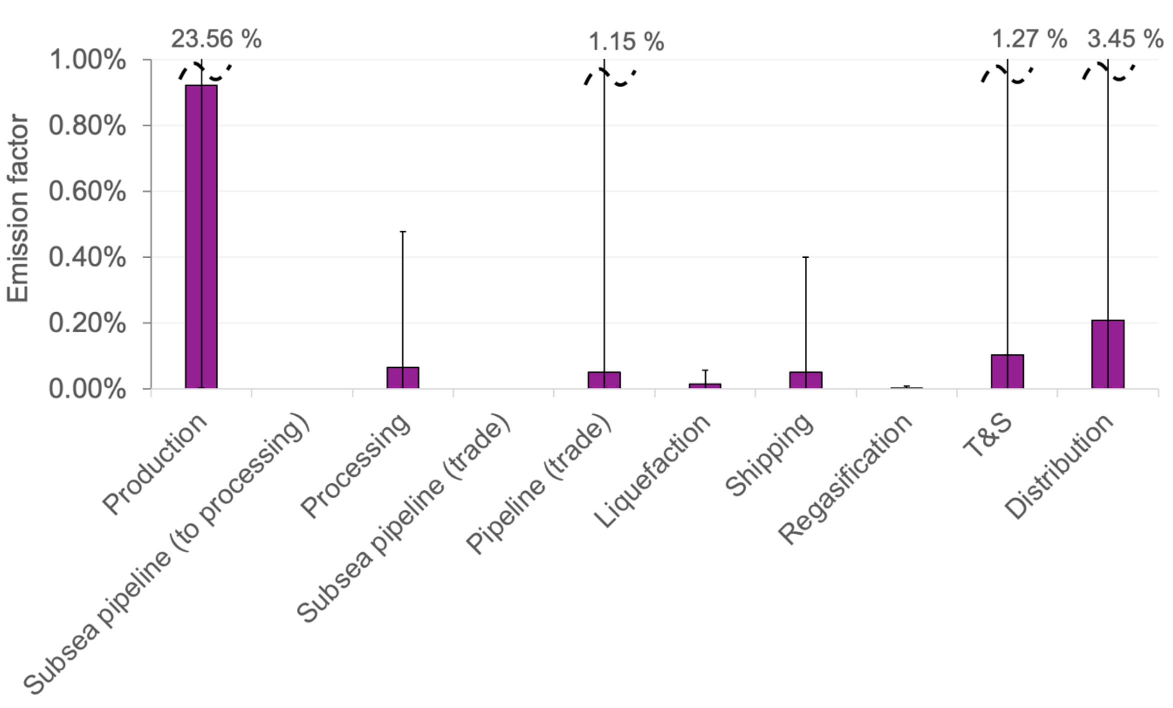

Figure 3: Emission factor for the stages in the gas supply chain. The bar represents the average emission factor across all the supply chains, and the error bars indicate the minimum and maximum. Please note that leaks from subsea pipelines are assumed to dissolve in seawater and do not reach the atmosphere. However, a recent study has found evidence that methane emissions from subsea oil and gas activities could reach the surface (Böttner et al., 2020).

3.2. Methane emissions (kt CH_4) and emissions intensities (%) across the 252 supply chains

Based on the data for 2017, a total of 26.4 megatonnes of methane (Mt CH_4), 14.5-48.2 Mt CH_4 when uncertainty bounds are considered, was emitted by the supply chains considered in this work: 15.5 Mt CH_4 (8.2-23.3 Mt CH_4) from production and processing, 7.8 Mt CH_4 (5.2-14.9 MT CH_4) from T&S and distribution and 3.1 Mt CH_4 (1.1-10.0 Mt CH_4) from trade (Figure 4). These are large quantities of methane, comparable to the 2017 GHG emissions of Germany, Indonesia, Spain and Qatar (when converted into Mt CO_{2eq} using a GWP of 34), respectively (Ritchie and Roser, 2019). There is a wide variation in emissions across supply chains and countries (Figures S2 and S3 in the SI). Overall, USA domestic production is the supply chain with the highest emissions, followed by Russian domestic consumption (Figure 4; see SI for emission estimates), but when comparing emissions intensity with kt CH_4 emitted by each supply chain (Figure 6), there is no correlation. When examining these two supply chains, they are large supply chains in terms of natural gas throughput, which resulted in the high amount of methane emitted despite having median emission intensity.

On average, 134 kt CH_4 was emitted by each supply chain (28 kt CH_4 normalised average), but a large proportion have emissions below average as shown in Figure 4 and Figure S2 in the SI. In general, emissions from domestic production and consumption are higher than emissions from trade. However, this is largely because most of the gas produced is consumed domestically; 31% of gas produced is traded. When traded gas is considered, countries which are heavy exporters or importers are also large emitters. The country of origin for imported gas will have a significant impact on emissions. For example, from Figure 4 it can be seen that

Italy has higher emissions from pipeline imports than Germany. This is in spite of Germany being the largest importer of pipeline gas in the world. Germany imports all its gas from Europe, while Italy imports a large percentage of its gas from North Africa.

When the emissions intensity (m^3 CH_4 emitter divided by total gas throughput) is considered, supply chains where there is a heavy dependence on Tier 1 emission factors have the highest emission intensity. The average intensity across the supply chains is 1.7% with an upper bound of 28.8% (0.7% normalised average), but most supply chains have lower intensity, as shown in Figure 5. A handful of supply chains have significantly higher emission intensities (e.g. Iranian pipeline imports, Malaysian LNG imports) which skews the average.

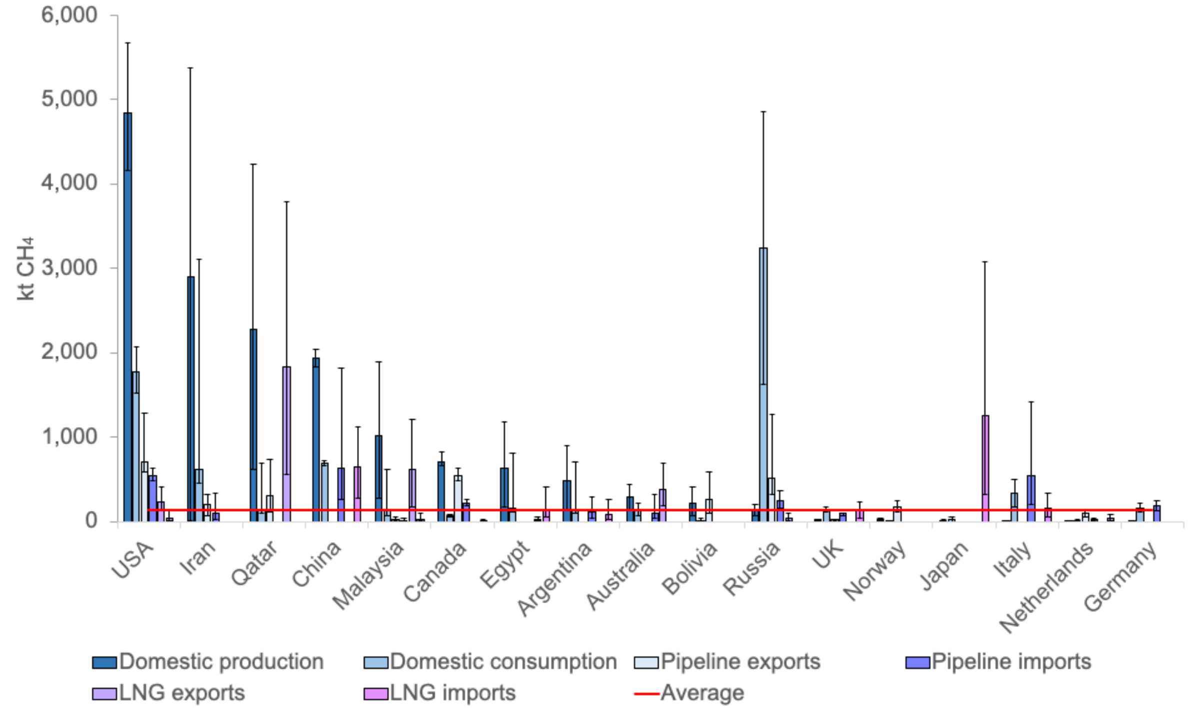

Figure 4: Methane emitted by the different types of supply chains. Domestic production considered the stages production and processing; domestic consumption considers the stages T&S and distribution; pipeline exports considers pipeline and downstream emissions, pipeline imports considers pipeline and upstream emissions; LNG exports considers liquefaction, shipping, regasification and downstream emissions; LNG imports considers liquefaction, shipping, regasification and upstream emissions. Please note that upstream and downstream emissions are only included in pipeline/LNG imports and exports for countries outside the 17 largest producers and consumers e.g., Algeria, Brunei, France. This is to avoid double counting. The bar indicates the average (across all supply chains, not the normalised average) and the minimum and maximum are shown by the error bars. Countries are ordered in sequential order by production emissions. For log scale version of the graph, see Figure S2 in the SI.

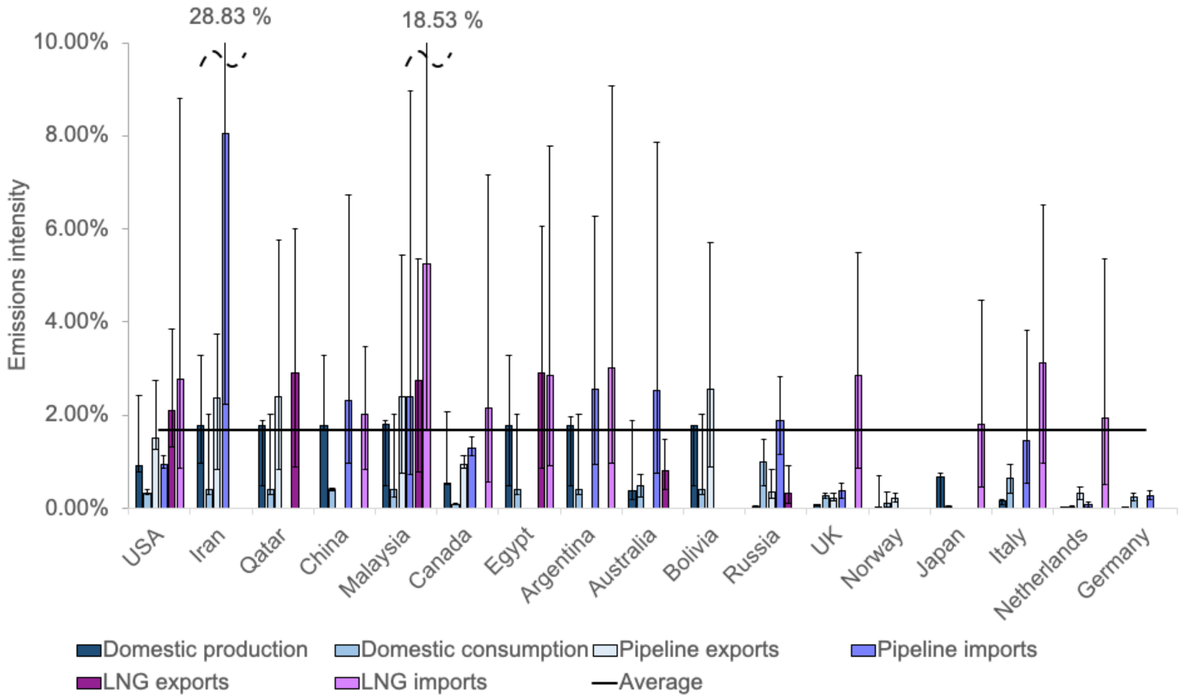

Figure 5: Emissions intensity, m^3 CH_4 divided by total gas throughput, for the different supply chains. The bar indicates the average (across supply chains and not the normalised average) and the minimum and maximum shown by the error bars. It should be noted that the exceptionally high emission intensity for Iranian pipeline imports is from imported Turkish gas. The value taken from the Turkish UNFCCC submission could be a typo- Turkey uses Tier 1 emission factors (0.05-3.32% for gas production and processing). The emissions estimated for each individual supply chain can be found in the SI

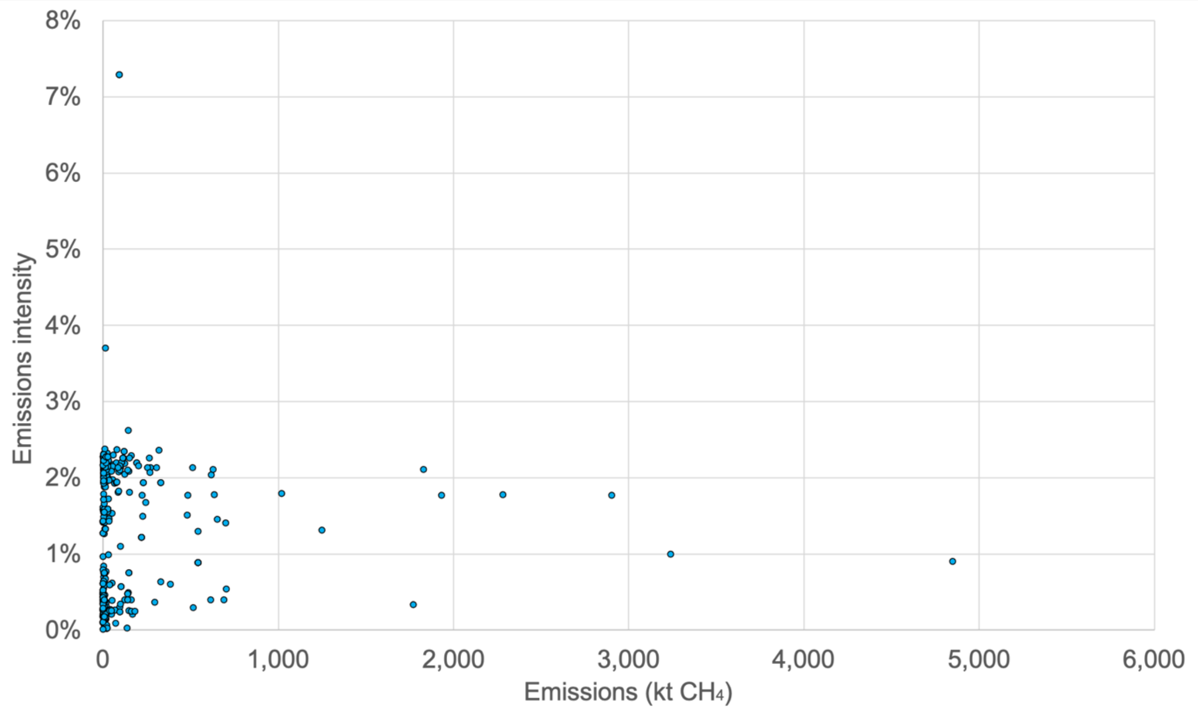

Figure 6: Comparison of emissions (kt CH_4) to emissions intensity (m^3 CH_4 divided by total gas throughput) of each supply chain considered. The poor correlation (R^2 value of 0.0006) between the two indicates that they are not dependant or related to one another.

3.2.1. Comparison of methane emission estimates with other literature

The results of this work have been compared to the data from the IEA Methane Tracker for the 17 countries considered. There are other databases and inventories which have estimated emissions from gas production and use e.g. European Commission's Emissions Database for Global Atmospheric Research (EDGAR) and Oil Climate Index (OCI) (EDGAR, 2020, OCI, 2019). However, these either consider a different year or give emission per gas basin/field and are therefore not considered for comparison with the results of this work.

A comparison has been made based on upstream and downstream emissions by country and in comparison, the results of this work are comparable (Figure 7). There is good agreement for most countries (IEA values within one standard deviation) but there are a few where there is a considerable difference. Norway's emissions are estimated to be 3.4-9.3 times smaller in this work than in the Methane Tracker. Upstream gas in Russia is also estimated to be lower (48-fold) than in the Methane Tracker, while downstream is 53% larger. The differences are largely due to different emission factors used. This work uses emission factors reported in submissions to the UNFCCC while the Methane Tracker uses process/equipment specific emission factors from the USA (IEA, 2020). While the USA emission factors are Tier 3, other countries have also developed their own Tier 3 emission factors, which are lower than the USA's e.g., Norway and Russia. Other countries use Tier 1 default emission factors which are higher than the USA emission factors e.g. Malaysia and Iran. These differences in data can account for the majority of variation between the results of this work and the Methane Tracker.

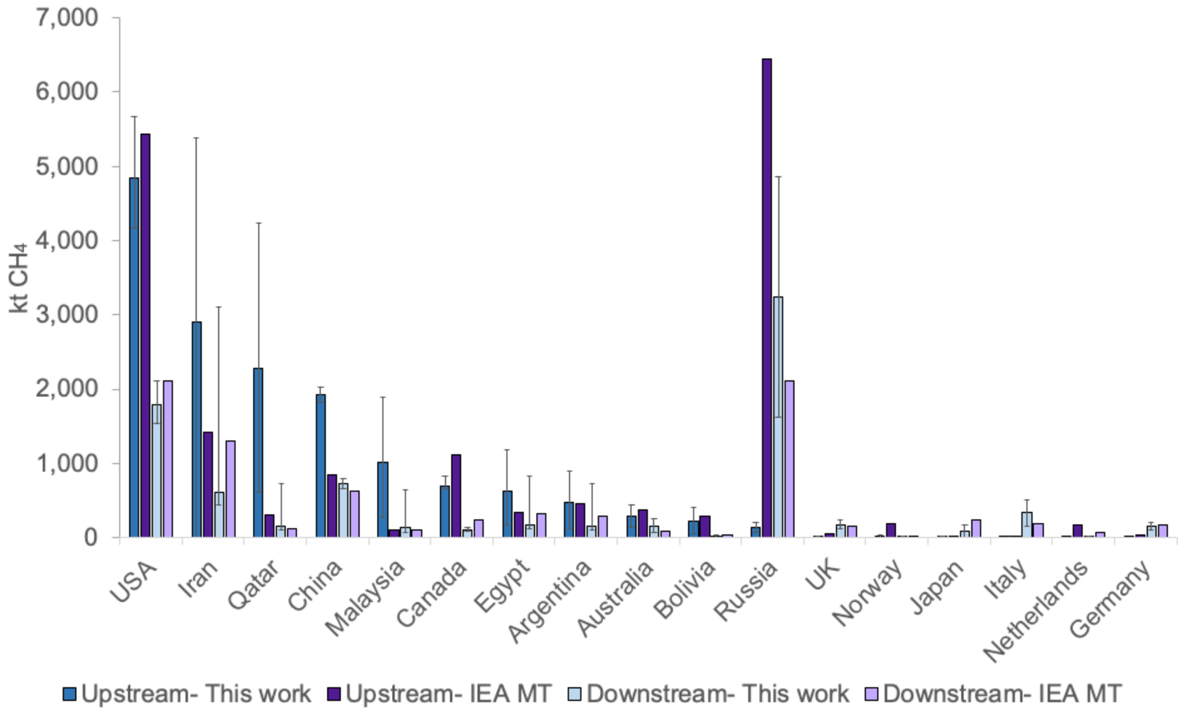

Figure 7: Comparison of this work's results with data from the IEA Methane Tracker (IEA MT) (IEA, 2020). The error bars indicate the minimum and maximum emissions calculated in this work.

3.3. Uncertainty in the emissions estimated

3.3.1. Consequential uncertainty via bootstrapping resampling

The impact of the high dependency on Tier 1 emission factors has been assessed through bootstrapping resampling. When resampled as is, the range in emission factors decreases while the average remained the same but when resampled omitting Tier 1, both the range and average decreased. The average emission factor for production decreases from 0.9% to 0.2% when resampled omitting Tier 1. Processing, T&S and distribution also experience decreases, but less drastic. See Sections 4 to 6 in the SI for more information.

When emissions from production, processing, T&S and distribution are recalculated using the resampled (omitting Tier 1) emission factors, emissions are 4.1 Mt CH_4 from both production and processing and T&S and distribution. This is a 3.8-fold decrease in upstream emissions and 47% reduction in downstream emissions, relative to the original estimates. While a significant decrease, this is still a large quantity emitted- comparable to the 2017 GHG emissions of Madagascar (Ritchie and Roser, 2019). The results suggest that the emissions estimated in the previous section could be an overestimate because of the high reliance on Tier 1 emission factors, particularly in the upstream stages. It also suggests that countries which rely solely on Tier 1 emission factors are likely to be inaccurately reporting their emissions.

3.3.2. 'Risk' of (unaccounted) high emissions

When risk of high emissions is considered, countries which reply on Tier 1 emission factors are at risk of high emissions, particularly high emissions being unaccounted for. The risk presented here is the product of the consequence of high emissions (relative to a 0.2% emissions intensity benchmark) and the likelihood of inaccurate emissions reporting. Given the high proportion of Tier 1 data used, this increased the risk for many countries as Tier 1 emission factors are much higher than the benchmark and they have higher likelihood of reporting inaccuracy because they are generic.

In total, 58% of countries are at high risk of high emissions in production and 40% at high risk of emissions in distribution (Figure 8). No countries are at high risk of high emissions in processing and distribution, but 56% and 43% of countries, respectively, are at moderate risk. This infers that many of the countries studied in this work could be inaccurately reporting their emissions. As most of the high risk countries use Tier 1 emission factors they are more likely to be overestimating their emissions rather than underestimate emissions as Tier 1 emission factors are conservative. However, these results are dependent on the assumption that Tier 2/3 emission factor data are accurate and countries are accurately reporting their emissions. The verification of emission factors by independent third-party organisations is not available for the majority of countries. Therefore, it is uncertain how accurate and transparent the emissions reporting is. Drawing from the comparisons with the IEA Methane Tracker in the previous section, while the overall comparisons is in agreement, there are countries where there is a significant difference e.g. Russia, Qatar and Norway. This discrepancy could infer that for these countries an additional degree of risk is present, which could infer a high risk of high emissions.

3.4. Emissions estimates- overall accuracy of our emission estimates

As countries are implementing methane strategies to curb their emissions, the accurate quantification and verification of emissions data are essential so that methane (and overall carbon) budgets are met in order for net-zero ambitions to be met. Overall, it appears there is a rather high degree of uncertainty in emission estimates. While the results of the bootstrapping resampling suggest that the Tier 1 emission factors could be resulting in an overestimate of emissions, the results of the risk assessment suggest a high percentage of countries could be at risk of high emissions. Therefore, it cannot be concluded whether the results estimated in the previous section are an over or underestimate. However, it is clear there is a high level of uncertainty in emission estimates, because of the large number of data gaps in emissions reporting. To reduce this uncertainty, more primary data is needed to reduce the reliance on Tier 1 emission factors.

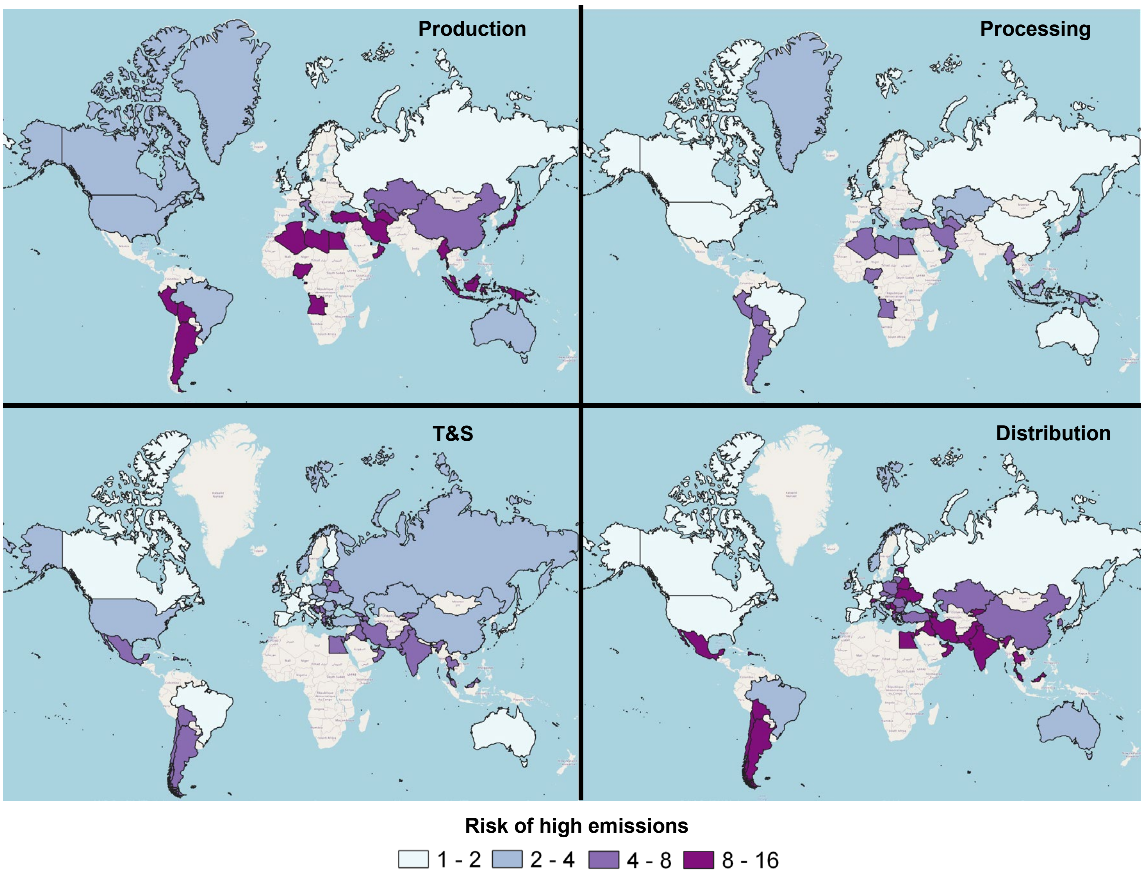

Figure 8: Risk assessment heat maps identifying regions at risk of high emissions: production, processing, T&S and distribution. 1-2 is no risk; 2-4 is low risk; 4-8 is moderate risk and 8-16 is high risk. It is important to note that the level of risk assessed here assumes that each country is accurately reporting their methane emissions in their national inventories.

4. Limitations of this work and areas for future work

The results of this work consider variations in emission factors only. The gas throughput (also known as the activity factor) would also affect emissions and is important as different datasets report different (but similar) values for gas volume. Also, some datasets aggregate gas volumes or do not specify the country which resulted in assumptions being made (Section 2). The composition of gas was not taken into consideration. While this will not have a significant impact on the overall results, the composition of gas is an important factor in developing emission factors.

The emissions estimated are for the largest gas producers and consumers and do not give an estimate of global gas production, consumption and trade. The results of this work could be extrapolated to supply chains not considered in this work, but this should be done and interpreted with caution. Future work should estimate emissions for the supply chains not considered in this work (the remaining 23 to 35% of global gas production, consumption and trade), as this would allow a global picture to be developed. The evolution of emissions over time is another area for further research. However, as only a handful of countries have emissions measurement data from pre-1998, this would limit the accuracy of such work.

5. Conclusions

This work has analysed emission factor data and estimated methane emissions for the world's largest natural gas producers and consumers. The uncertainty in emission estimates was assessing using bootstrapping resampling, with a focus on determining the impact of Tier 1 emission factors. Areas at risk of high emissions were identified through a risk assessment.

We estimate 26.4 Mt CH_4 to have been emitted in 2017 by all 252 supply chains considered. 15.5 Mt CH_4 was emitted from upstream production and processing, 7.8 Mt CH_4 from downstream T&S and distribution and 3.1 Mt CH_4 from trade (pipeline transport and LNG liquefaction, shipping and regasification). The average emissions emitted by a supply chain is 134 kt CH_4 (28 kt CH_4 normalised average) but there is a large variation, ranging from >1,000 kt CH_4 to <0.1 kt CH_4. The emissions intensity also varies, ranging from 0.01% to 8.1%, averaging at 1.7% (0.7% normalised average) but the majority of supply chains have lower emissions. Both a high emissions intensity and large gas throughput resulted in large emissions and we found no correlation between emissions and emissions intensity, which suggests that poor emissions management cannot be attributed to either independently.

Our results showed that there is high uncertainty in emission estimates and that a large proportion of the countries we assessed are at high risk of (unaccounted) high emissions. When assessing the emissions data, we found that there is a high reliance (72% of emission factor data collected) on Tier 1 emission factors. When the emissions data was resampled, omitting the Tier 1 data, we found that supply chain emissions decreased by 3.8-fold upstream and 47% downstream. This suggests that emissions estimated using Tier 1 data could be an overestimate and any country which solely relies on this data is at risk of inaccurate emission estimates. However, the risk assessment indicated a significant proportion of countries to be at high risk of high emissions. We were unable to deduce whether our emissions estimates are an over or underestimate, as we were unable to determine how representative or accurate Tier 1 data is to the countries which use it.

Overall, the findings of this work suggest the largest gas supply chains are significant sources of methane. The methane emitted, when converted into Mt CO_{2eq}, are comparable to major countries (e.g. Germany and Spain). However, there is a high degree of uncertainty in the estimates, primarily related to the high dependence on Tier 1 emission factor data. More efforts should be put into collecting emissions data and improve the transparency in reporting to increase the certainty in emission estimates. These would aid in better emission accounting and allow for effective emission abatement strategies to be developed.

CRediT authorship contribution statement
Jasmin Cooper: Conceptualization, Methodology, Formal analysis, Investigation, Writing- Original Draft, Writing- Review & Editing, Visualization, Project administration. **Paul Balcombe:** Conceptualization, Writing- Review & Editing. **Adam Hawkes:** Conceptualization, Writing- Review & Editing

Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Allen, D. T., Torres, V. M., Thomas, J., Sullivan, D. W., Harrison, M., Hendler, A., Herndon, S. C., Kolb, C. E., Fraser, M. P., Hill, A. D., Lamb, B. K., Miskimins, J., Sawyer, R. F. & Seinfeld, J. H. 2013. Measurements of methane emissions at natural gas production sites in the United States. *Proceedings of the National Academy of Sciences,* 110**,** 17768-17773. *10.1073/pnas.1304880110*

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Davis, K. J., Herndon, S. C., Jacob, D. J., Karion, A., Kort, E. A., Lamb, B. K., Lauvaux, T., Maasakkers, J. D., Marchese, A. J., Omara, M., Pacala, S. W., Peischl, J., Robinson, A. L., Shepson, P. B., Sweeney, C., Townsend-Small, A., Wofsy, S. C. & Hamburg, S. P. 2018. Assessment of methane emissions from the U.S. oil and gas supply chain. *Science,* 361**,** 186. *10.1126/science.aar7204*

Balcombe, P., Brandon, N. P. & Hawkes, A. D. 2018a. Characterising the distribution of methane and carbon dioxide emissions from the natural gas supply chain. *Journal of Cleaner Production,* 172**,** 2019-2032. *https://doi.org/10.1016/j.jclepro.2017.11.223*

Balcombe, P., Speirs, J. F., Brandon, N. P. & Hawkes, A. D. 2018b. Methane emissions: choosing the right climate metric and time horizon. *Environmental Science: Processes & Impacts,* 20**,** 1323-1339. *10.1039/C8EM00414E*

Böttner, C., Haeckel, M., Schmidt, M., Berndt, C., Vielstädte, L., Kutsch, J. A., Karstens, J. & Weiß, T. 2020. Greenhouse gas emissions from marine decommissioned hydrocarbon wells: leakage detection, monitoring and mitigation strategies. *International Journal of Greenhouse Gas Control,* 100**,** 103119. *https://doi.org/10.1016/j.ijggc.2020.103119*

BP. 2019. BP statistical review of world energy - 2019, London, UK; *British Petroleum (BP). Available:'* https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

Caulton, D. R., Shepson, P. B., Santoro, R. L., Sparks, J. P., Howarth, R. W., Ingraffea, A. R., Cambaliza, M. O. L., Sweeney, C., Karion, A., Davis, K. J., Stirm, B. H., Montzka, S. A. & Miller, B. R. 2014. Toward a better understanding and quantification of methane emissions from shale gas development. *Proceedings of the National Academy of Sciences,* 111**,** 6237-6242. *10.1073/pnas.1316546111*

Conley, S., Franco, G., Faloona, I., Blake, D. R., Peischl, J. & Ryerson, T. B. 2016. Methane emissions from the 2015 Aliso Canyon blowout in Los Angeles, CA. *Science,* 351**,** 1317-1320. *10.1126/science.aaf2348*

Cui, Y. Y., Brioude, J., Angevine, W. M., Peischl, J., McKeen, S. A., Kim, S.-W., Neuman, J. A., Henze, D. K., Bousserez, N., Fischer, M. L., Jeong, S., Michelsen, H. A., Bambha, R. P., Liu, Z., Santoni, G. W., Daube, B. C., Kort, E. A., Frost, G. J., Ryerson, T. B., Wofsy, S. C. & Trainer, M. 2017. Top-down estimate of methane emissions in California using a mesoscale inverse modeling technique: The San Joaquin Valley. *Journal of Geophysical Research: Atmospheres,* 122**,** 3686-3699. *10.1002/2016jd026398*

Cui, Y. Y., Brioude, J., McKeen, S. A., Angevine, W. M., Kim, S.-W., Frost, G. J., Ahmadov, R., Peischl, J., Bousserez, N., Liu, Z., Ryerson, T. B., Wofsy, S. C., Santoni, G. W., Kort, E. A., Fischer, M. L. & Trainer, M. 2015. Top-down estimate of methane emissions in California using a mesoscale inverse modeling technique: The South Coast Air Basin. *Journal of Geophysical Research: Atmospheres,* 120**,** 6698-6711. *10.1002/2014jd023002*

EDF. 2019. *Methane: The other important greenhouse gas* [Online]. New York, NY, USA: Environmental Defence fund (EDF). Available: https://www.edf.org/climate/methane-other-important-greenhouse-gas [Accessed August 2019].

EDF 2020. Permian Methane Analysis Project (PermianMAP). New York, NY, USA: Environmental Defense Fund (EDF).

EDGAR 2020. EDGAR v5.0 Global Greenhouse Gas Emissions. Brussels, BE: European Commissions Joint Research Centre.

European Commission. 2020. EU Methane Strategy, Brussels, BE; *European Union (EU). Available:'* https://ec.europa.eu/energy/sites/ener/files/eu_methane_strategy.pdf
Exergia. 2015. Study on actual GHG data for diesel, petrol, kerosene and natural gas, Brussels, BE; *Exergia. Available:'* https://ec.europa.eu/energy/sites/ener/files/documents/Study%20on%20Actual%20GHG%20Data%20Oil%20Gas%20Final%20Report.pdf
Fox, T. A., Barchyn, T. E., Risk, D., Ravikumar, A. P. & Hugenholtz, C. H. 2019. A review of close-range and screening technologies for mitigating fugitive methane emissions in upstream oil and gas. *Environmental Research Letters,* 14. *10.1088/1748-9326/ab0cc3*
Gazprom. 2018. PJSC Gazprom Annual Report, Moscow, RU; *Gazprom. Available:'* https://www.gazprom.com/about/marketing/cis-baltia/
GMI. 2020. *UNEP: Oil and Gas Methane Partnership Initiative to Manage Methane Emissions from Upstream Oil and Gas Operations* [Online]. Global Methane Initiative (GMI). Available: https://globalmethane.org/challenge/ogmp.html [Accessed October 2020].
Hausfather, Z. 2020. UNEP: Net-zero pledges provide an 'opening' to close growing emissions 'gap'. *Carbon Brief*.
IEA 2020. Methane Tracker. Paris, FR: International Energy Agency.
IEA. 2021. Driving Down Methane Leaks from the Oil and Gas Industry, Paris, FR; *Internatioanl Energy Agency (IEA). Available:'* https://www.iea.org/reports/driving-down-methane-leaks-from-the-oil-and-gas-industry
IGU. 2018. 2018 World LNG Report, Barcelona, ES; *International Gas Union (IGU). Available:'* https://www.igu.org/publication/301694/31
IPCC. 2003. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Geneva, CH; *Intergovernmental Panel on Climate Change (IPCC). Available:'* https://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html
IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Kanagawa, JP; *Prepared by the National Greenhouse Gas Inventories Programme. Available:'* https://www.ipcc-nggip.iges.or.jp/public/2006gl/
Kang, M., Kanno, C. M., Reid, M. C., Zhang, X., Mauzerall, D. L., Celia, M. A., Chen, Y. & Onstott, T. C. 2014. Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. *Proceedings of the National Academy of Sciences***,** 201408315. *10.1073/pnas.1408315111*
Kort, E. A., Frankenberg, C., Costigan, K. R., Lindenmaier, R., Dubey, M. K. & Wunch, D. 2014. Four corners: The largest US methane anomaly viewed from space. *Geophysical Research Letters,* 41**,** 6898-6903. *10.1002/2014gl061503*
Lammey, M. 2020. BP invests $5m as part of crusade against methane leaks *Energy Voice*, 23 June 2020.
Marchese, A. J., Vaughn, T. L., Zimmerle, D. J., Martinez, D. M., Williams, L. L., Robinson, A. L., Mitchell, A. L., Subramanian, R., Tkacik, D. S., Roscioli, J. R. & Herndon, S. C. 2015. Methane Emissions from United States Natural Gas Gathering and Processing. *Environmental Science & Technology,* 49**,** 10718-10727. *10.1021/acs.est.5b02275*
MARCOGAZ. 2017. Survey methane emissions for gas distribution in Europe, Brussels, BE; *MARCOGAZ. Available:'* https://www.marcogaz.org/app/download/7926774363/WG-ME-17-25.pdf?t=1541592032
MARCOGAZ. 2018. Survey of methane emissions from LNG terminals in Europe, Brussels, BE; *MARCOGAZ. Available:'* https://www.marcogaz.org/app/download/7926786463/WG-ME-17-22.pdf?t=1541592018.
Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, Takemura, T. & Zhang, H. 2013. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *In:* STOCKER, T. F., D. QIN, G.-K. PLATTNER, M. TIGNOR, S.K. ALLEN, J.

BOSCHUNG, A. NAUELS, Y. XIA, BEX, V. & MIDGLEY, P. M. (eds.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
Nowlan, A. 2017. Shell becomes latest oil and gas company to test smart methane sensors [Blog]. *Energy Exchange* [Online]. Available from: http://blogs.edf.org/energyexchange/2017/08/09/shell-becomes-latest-oil-and-gas-company-to-test-smart-methane-sensors/ [Accessed 9th August 2017 February 2020].
OCI 2019. OCI+ Gas Preview. 2019 ed. Washington D.C., USA: Oil Climate Index (OCI).
OGCI. 2018a. At Work- Committed to climate change, London, UK; *Oil and Gas Climate Initiative (OGCI). Available:'* https://oilandgasclimateinitiative.com/wp-content/uploads/2018/09/OGCI_Report_2018.pdf
OGCI. 2018b. *Oil and Gas Climate Initiative sets first collective methane target for member companies* [Online]. New York, NY, USA: Oil and Gas Climate Initiative (OGCI). Available: https://oilandgasclimateinitiative.com/oil-and-gas-climate-initiative-sets-first-collective-methane-target-for-member-companies/ [Accessed June 2020].
Oonk, H. & Vosbeek, M. 1995. Quantification of methane emissions in the exploration and production of natural gas and petroleum in The Netherlands. *In:* ZWERVER, S., VAN ROMPAEY, R. S. A. R., KOK, M. T. J. & BERK, M. M. (eds.) *Studies in Environmental Science.* Elsevier.
Ravikumar, A. P., Wang, J., McGuire, M., Bell, C. S., Zimmerle, D. & Brandt, A. R. 2018. "Good versus Good Enough?" Empirical Tests of Methane Leak Detection Sensitivity of a Commercial Infrared Camera. *Environmental Science & Technology,* 52**,** 2368-2374. *10.1021/acs.est.7b04945*
Ravikumar, A. R., Sreedhara, S., Wang, J. F., Englander, J., Roda-Stuart, D., Bell, C., Zimmerle, D., Lyon, D., Mogstad, I., Ratner, B. & Brandt, A. R. 2019. Single-blind inter-comparison of methane detection technologies - results from the Stanford/EDF Mobile Monitoring Challenge. *Elementa-Science of the Anthropocene,* 7**,** 16. *10.1525/elementa.373*
Ritchie, H. & Roser, M. 2019. CO_2 and Greenhouse Gas Emissions, *Our World in Data. Available:'* https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions
Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., Raymond, P. A., Dlugokencky, E. J., Houweling, S., Patra, P. K., Ciais, P., Arora, V. K., Bastviken, D., Bergamaschi, P., Blake, D. R., Brailsford, G., Bruhwiler, L., Carlson, K. M., Carrol, M., Castaldi, S., Chandra, N., Crevoisier, C., Crill, P. M., Covey, K., Curry, C. L., Etiope, G., Frankenberg, C., Gedney, N., Hegglin, M. I., Höglund-Isaksson, L., Hugelius, G., Ishizawa, M., Ito, A., Janssens-Maenhout, G., Jensen, K. M., Joos, F., Kleinen, T., Krummel, P. B., Langenfelds, R. L., Laruelle, G. G., Liu, L., Machida, T., Maksyutov, S., McDonald, K. C., McNorton, J., Miller, P. A., Melton, J. R., Morino, I., Müller, J., Murguia-Flores, F., Naik, V., Niwa, Y., Noce, S., O'Doherty, S., Parker, R. J., Peng, C., Peng, S., Peters, G. P., Prigent, C., Prinn, R., Ramonet, M., Regnier, P., Riley, W. J., Rosentreter, J. A., Segers, A., Simpson, I. J., Shi, H., Smith, S. J., Steele, L. P., Thornton, B. F., Tian, H., Tohjima, Y., Tubiello, F. N., Tsuruta, A., Viovy, N., Voulgarakis, A., Weber, T. S., van Weele, M., van der Werf, G. R., Weiss, R. F., Worthy, D., Wunch, D., Yin, Y., Yoshida, Y., Zhang, W., Zhang, Z., Zhao, Y., Zheng, B., Zhu, Q., Zhu, Q. & Zhuang, Q. 2020. The Global Methane Budget 2000–2017. *Earth Syst. Sci. Data,* 12**,** 1561-1623. *10.5194/essd-12-1561-2020*
Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M. & Bovensmann, H. 2014. Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations. *Earth's Future,* 2**,** 548-558. *10.1002/2014ef000265*
SEA-DISTANCES.ORG. 2019. *Port Distances* [Online]. Available: https://sea-distances.org/ [Accessed September 2019].
Speirs, J., Balcombe, P., Blomerus, P., Stettler, M., Brandon, N. & Hawkes, A. 2019. Can natural gas reduce emissions from transport? Heavy goods vehicles and shipping, London, UK; *Sustainable Gas Institute, Imperial College London. Available:'*

https://www.sustainablegasinstitute.org/dissemination-can-natural-gas-reduce-emissions-in-the-transport-sector-heavy-goods-vehicles-and-shipping/
thinkstep. 2017. Greenhouse gas intensity of natural gas Stuttgart, DE; *thinkstep. Available:'* http://ngvemissionsstudy.eu/
Tokyo Gas. 2018. *Environmental Data* [Online]. Tokyo, JP. Available: https://tokyo-gas.disclosure.site/en/themes/131 [Accessed September 2019].
UNFCCC. 2019a. *National Communication submissions from Non-Annex I Parties* [Online]. UNFCCC. Available: https://unfccc.int/non-annex-I-NCs [Accessed May 2021].
UNFCCC. 2019b. *National Inventory Submissions 2019* [Online]. Bonn, DE: United Nations Framework Convention on Climate Change (UNFCCC). Available: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2019 [Accessed September 2019].
UNFCCC. 2020a. *Biennial Update Report submissions from Non-Annex I Parties* [Online]. Bonn, DE: United Nations Framework Convention on Climate Change (UNFCCC). Available: https://unfccc.int/BURs [Accessed September 2019].
UNFCCC. 2020b. *National Communication submissions from Non-Annex I Parties* [Online]. Bonn, DE: United Nations Framework Convention on Climate Change (UNFCCC). Available: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-communications-and-biennial-update-reports-non-annex-i-parties/national-communication-submissions-from-non-annex-i-parties [Accessed September 2019].
UNFCCC. 2020c. *National Inventory Submissions 2019* [Online]. Bonn, DE: United Nations Framework Convention on Climate Change (UNFCCC). Available: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2019 [Accessed September 2019].
Xu, M., Aizhu, C. & Jacob-Phillips, S. 2020. China's CNPC targets 50% slash in methane emission intensity by 2025. *Reuters*, 2 July 2020.
Zhang, Y., Gautam, R., Pandey, S., Omara, M., Maasakkers, J. D., Sadavarte, P., Lyon, D., Nesser, H., Sulprizio, M. P., Varon, D. J., Zhang, R., Houweling, S., Zavala-Araiza, D., Alvarez, R. A., Lorente, A., Hamburg, S. P., Aben, I. & Jacob, D. J. 2020. Quantifying methane emissions from the largest oil-producing basin in the United States from space. *Science Advances,* 6**,** eaaz5120. *10.1126/sciadv.aaz5120*