Natural gas and climate change

Date: 17th October 2017
Prepared by: Prof Kevin Anderson, University of Manchester & Uppsala University
Dr John Broderick, University of Manchester & Teesside University

Acknowledgements

1   Introduction

1.1   Context

The Paris Agreement, building on previous international commitments, clearly sets out common goals to keep "the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels". At an EU level, existing targets must now be further tightened to ensure the EU's "fair" contribution, quantified "on the basis of equity" and in accordance with the "best science", meets the more ambitious commitments in the new agreement.

Natural gas has been presented as a "bridging fuel" that can play an important role in facilitating the transition to a low carbon economy, complementing a significant increase in the utilisation of renewable energy sources. In order to quantify the maximum level of EU natural gas consumption compatible with existing EU targets and the Paris Agreement, the relative lifecycle carbon intensity of a range of potential natural gas sources must be more fully understood, particularly methane leakage.

1.2   Summary

By 2035 the substantial use of fossil fuels, including natural gas, within the EU's energy system will be incompatible with the temperature commitments enshrined in the Paris Agreement.

The following paragraphs summarise the basis for this conclusion.

1) The Paris commitment will be exceeded in under 18 years of current greenhouse gas emissions
With a rapid decline in deforestation and prompt reductions in process emissions from cement production, the post-2017 energy-only *global* carbon budget necessary to deliver on the Paris temperature commitments ranges from around 490 to 640 billion tonnes ($GtCO_2$); this includes all forms of energy consumption, from transport to electricity. At current rates of emissions from energy this relates to between 14 years, for an "unlikely" chance of 1.5°C, and 18 years, for a "likely" chance of 2°C.

2) Non-OECD nations will "fairly" use up to 98% of the 2°C global carbon budget
Assuming a peak in energy carbon emissions from the non-OECD region occurs between 2020 and 2025 (far earlier than anything countenanced in Paris), and that this is followed by escalating rates of mitigation towards 10% p.a. twenty two years after the peak emissions year, then the non-OECD energy-only emissions post-2017 extend from 502 $GtCO_2$ to 620 $GtCO_2$.

3) It is highly unlikely that the Paris 1.5°C commitment is a viable mitigation objective
From #1 and #2 above it is evident that it is no longer viable to mitigate emissions at a global level so as to deliver on the Paris commitment "*to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels*" (NB see #3a).

3a) A well resourced RD&D programme on NETs holds out only a small & rapidly vanishing chance of 1.5°C
Only if "real" mitigation guided by the carbon budgets for a "likely" chance of 2°C are pursued and highly speculative negative emissions technologies prove to be successful at an early and unprecedented planetary scale, could 1.5°C be considered theoretically achievable.

4) Current levels of emissions will use up the EU's 2°C carbon budget in under nine years

Combining the Paris equity criteria with the small and fast dwindling global carbon budget for 2°C (see #1) leaves the EU facing a profound mitigation challenge. For the EU to make its minimum "fair" contribution to the Paris "*well below 2°C*" commitment, its post-2017 energy-only carbon budgets should be between 23 and 32GtCO$_2$, or approximately six to nine years of current EU energy-only emissions. This conclusion depends on a successful and highly ambitious mitigation agenda for non-OECD nations, far beyond their respective Nationally Determined Contributions; (i.e. an aggregate peak in non-OECD emissions between 2022 and 2023 with 10% mitigation each year by 2045 and over 95% cut in emissions (c.f. 2015) by the early 2060s. Anything less than this would impose still greater mitigation rates on the OECD and EU).

5) To meet its Paris 2°C commitment the EU needs over 12% p.a. mitigation, starting immediately

Assuming a highly optimistic mitigation agenda is actioned by the global community, then for the EU to deliver on its 2°C commitment it needs to begin an immediate programme of profound mitigation at a minimum rate of 12% p.a. in absolute emissions. Any delay in starting, or in pursuing a rate below 12% p.a., will either put a "likely" chance of 2°C beyond reach or require still more fundamental mitigation over the following years (see Appendix A).

This level of mitigation is far beyond the EU's headline Nationally Determined Contribution target of a 40% reduction in emissions by 2030. The EU's current position essentially ignores any reasonable interpretation of equity and is informed by scenarios that assume the huge uptake of so-called 'negative emission technologies' (NETs) and the direct removal of many 100s of billions of tonnes of carbon dioxide directly from the atmosphere. In addition, emissions arising from the EU's international aviation and shipping sectors are also excluded from the inventory used to estimate its mitigation commitments.

6) To deliver on the Paris commitments, policy makers need a balanced portfolio of CO2 mitigation scenarios with 'negative emissions technologies' only included in the exotic minority

The ubiquitous and global-scale inclusion of highly speculative 'negative emission technologies' (NETs) in global and national mitigation scenarios is dangerously weighting the policy-terrain in favour of technocratic-only responses. This endemic bias unreasonably lends support for the continued and long-term use of gas and oil whilst effectively closing down more challenging but essential debates over lifestyles, profound social-economic change and deeper penetration of genuinely decarbonised energy supply.

7) Methane emissions and atmospheric concentrations are observed at the top end of IPCC scenarios. Recent empirical studies of fossil fuel producing areas have found official inventories reported by governments to be under estimates for the areas surveyed

Large uncertainties remain on the sources of methane in the atmosphere. Measurement campaigns focussing on US oil and gas production have identified discrepancies between "top-down" atmospheric methods of quantifying emissions and official inventories of emissions based on "bottom–up" methods. It appears that methane emissions from the natural gas supply chain are dominated by low numbers of high intensity assets or events, making representative sampling difficult. There are therefore justifiably large ranges in the estimates for general supply chain types.

8) Emissions metrics are necessary for aggregating different greenhouse gas emissions produced by supply chains. Weighting methane emissions at 34x that of CO$_2$ is adequate for assessing the climate impact of natural gas in relation to the Paris Agreement's long-term climate stabilisation objectives

Natural gas production and consumption entails substantial emissions of both carbon dioxide and methane. These gases have different effects on the climate, methane predominantly causing short term warming, over one or two decades, and carbon dioxide having a much longer term effect, over hundreds of years. Reporting the impact of natural gas supply chains requires metrics that relate the different warming effects due to methane and carbon dioxide. These metrics have different scientific foundations and different value judgements and their choice must be appropriate to the policy question under consideration.

9) Carbon dioxide from combustion is the dominant contributor to the long-term climate change impact of natural gas. Methane has a much greater warming effect than carbon dioxide per unit of emissions released but its atmospheric lifetime is short, only about a decade. However, persistently high emissions of methane would replenish this loss and maintain this initial warming effect

Although short lived, if total anthropogenic methane emissions were to persist at current rates they would cause a significant temperature change of approximately 0.6°C. The production and distribution of natural gas releases methane both deliberately and inadvertently. The exact amount varies widely across locations and production technologies, and through time at a given location. Close monitoring shows that in most supply chains a small number of sites, or pieces of equipment, are responsible for a large proportion of methane emissions, however, they are difficult to identify *a priori*. Leakage rates affect the relative contribution of methane to the climate change impact of natural gas supply chains. They do not, however, dominate the long-term temperature change caused by a given quantity of natural gas production, as it is the CO$_2$ emissions that persist in the atmosphere over the long term.

9a) Liquefied Natural Gas (LNG) transport increases the climate change impact of natural gas supply chains

LNG transport requires additional energy intensive steps adding a further CO$_2$ burden. Estimates of greenhouse gas emissions from LNG supply chains are nearly double those of average pipeline supply chains. Long distance pipelines, e.g. from Russia, may have higher emissions than average but these are poorly measured at present.

10) For stabilising at 2°C, reductions in methane emissions must be accompanied by CO$_2$ reductions

Whilst mitigating short lived climate pollutants (SLCPs) such as methane is important, it must not detract from eliminating long-lived greenhouse gases, principally carbon dioxide.

11) Fossil fuels (including natural gas) have no substantial role in an EU 2°C energy system beyond 2035

The Paris 2°C and equity commitments, buttressed with the IPCC's carbon budgets, demand a minimum reduction in EU energy-only carbon emissions of around 95% by 2035 (c.f. 2015). Consequently, within two decades fossil fuel use, including gas, must have all but ceased, with complete decarbonisation following soon after. Prior work has shown that such a programme of mitigation requires significantly more than two thirds of existing reserves to remain in the ground. In this context and assuming an immediate 12% p.a. mitigation path, (or rising mitigation to around 18% by 2023; see Appendix A), there is categorically no role for bringing additional fossil fuel reserves, including gas, into production. This conclusion is not significantly affected by the prospect of carbon capture and storage, where the limitations on deployment rates and likely upstream methane emissions substantially restrict its potential, even with a conservative reading of the Paris 2°C commitment, a rejection of 1.5°C and a weak interpretation of equity. An urgent programme to phase out existing natural gas and other fossil fuel use across the EU is an imperative of any scientifically informed and equity-based policies designed to deliver on the Paris Agreement.

Contents

2 Carbon budgets for the EU based on the Paris Agreement

This section of the report translates the temperature and equity commitments enshrined in the Paris Agreement into a range of post 2017 carbon budgets for the European Union (EU). To appropriately understand and contextualise the conclusions of this section, it is important to be cognisant of the principal assumptions underpinning the analysis:

1) A very conservative reading of the Paris commitments; the conclusions should therefore be understood as erring towards a highly optimistic range of carbon budgets and a minimum level of mitigation.

2) All other major emitters will make their respective contribution to reducing emissions in line with, as a minimum, a similar reading of the Paris commitments (i.e. there are no significant "free riders").

3) No Negative Emission Technologies (NETs) are used to extend the carbon budget ranges (i.e. to make the mitigation challenge less onerous). All of the NETs remain unproven and highly speculative in regard to the scale of carbon dioxide removal they will be able to deliver. Moreover, there remains considerable uncertainty as to the wider environmental, social and justice implications of NETs applied at the level assumed in virtually all 2°C mitigation scenarios. This is particularly the case for Bioenergy with Carbon Capture and Storage (BECCS) - the NET of choice across the modelling community. See Box 1 for a fuller account of the decision to exclude NETs from this analysis.

   3a) It would be prudent to pursue a well resourced international R&D programme on the emission reduction potential and implications of NETs. However, mitigation for 2°C should be based on "real" reductions in emissions and thereby explicitly exclude NETs. Given that the Paris commitment extends to 1.5°C, the widespread inclusion of NETs at any significant level represents a serious moral hazard. Assuming that NETs work at large scale reduces the near-term mitigation effort required of wealthy high emitting nations, whilst the significant risk of NETs failing (i.e. much more severe climate impacts) falls primarily on poor, climate vulnerable and typically low-emitting communities.

4) No carbon cycle feedbacks, outside those included in the model runs underpinning the IPCC's carbon budgets, are included, i.e. the carbon budgets are not reduced through issues such as methane emissions from melting permafrost or additional soil metabolism as temperatures rise.[1] Whilst such feedbacks may be important and, on aggregate, risk significantly reducing the available carbon budget for anthropogenic emissions, their quantitative impact remains too uncertain to be included here. Consequently, the budgets and mitigation rates calculated within this report should be viewed as an optimistic interpretation of the science.

5) Emissions of carbon dioxide from deforestation are, across the century, matched by carbon sequestration through Land Use, Land Use Change and Forestry (LULUCF) activities.

6) Emissions from international aviation and shipping are included in the EU (and other regional) carbon budgets. If these emissions were to be considered separately (e.g. the responsibility of the International Maritime Organisation, IMO and the International Civil Aviation Authority, ICAO) then the requisite twenty-first century carbon budgets would need to be removed from each region.

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[1] For example: http://www.nature.com/nature/journal/v540/n7631/abs/nature20150.html

BOX 1: Negative emission technologies & 2°C scenarios

Virtually all of the 2°C scenarios within the IPCC's database include negative emissions technologies removing several hundred billion tonnes of carbon dioxide directly from the atmosphere across, and beyond, the century (Figure 1). However, there is wide recognition that the efficacy and global rollout of such technologies are highly speculative, with a non-trivial risk of failing to deliver at, or even approaching, the scales typically assumed in the models.

Whilst the authors of this report are supportive of funding further research, development and, potentially, deployment of NETs, the assumption that they will significantly extend the carbon budgets is a serious moral hazard (Anderson & Peters, 2016). Ultimately, if there is genuine action to mitigate emissions in line with a "likely" chance of staying below 2°C, and NETs do prove to be a viable and scalable option, then, in theory at least, an opportunity arises for holding the temperature rise to 1.5°C. By contrast, if action to mitigate for 2°C is undermined by the prospect of NETs, and such technologies subsequently prove not to be scalable, then we will have bequeathed a 3°C, 4°C or higher legacy. As is clear from the 2°C scenarios submitted to the IPCC, the inclusion of carbon capture and storage (CCS) and biomass energy with carbon capture and storage (BECCS) include considerably more fossil fuel combustion than those without them. It is evident, that mitigation advice to government is already being influenced by assumptions about NETs, and indeed the rapid uptake of CCS, neither of which shows any sign of approaching the scales of rollout in the models.
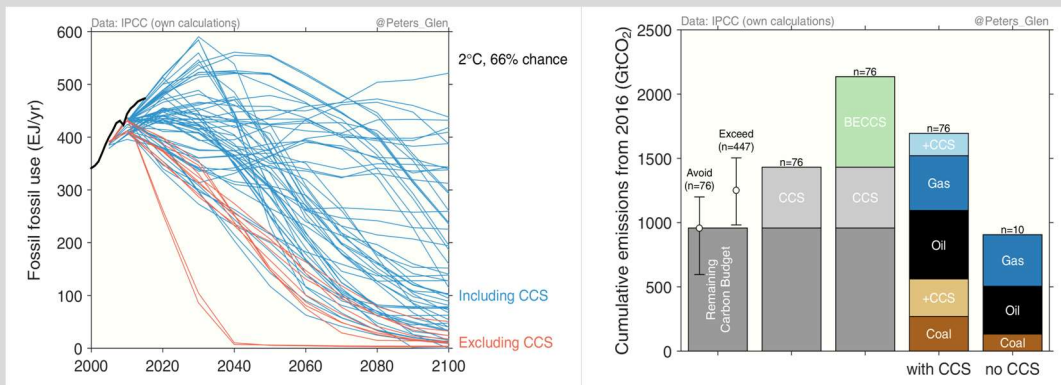
Figure 1 Emissions pathways based on the IPCC scenarios for a 66-100% chance of staying below 2°C, illustrate how the inclusion of CCS (and by definition BECCS) result in much more fossil fuel use. NB Figures provided by Glen Peters (Cicero), to be cleared before publication.

If the huge uptake of very uncertain NETs were the exception amongst mitigation scenarios, it would be of value. However, evoking global-scale NETs as a viable substitute to emissions reduction, which is much more challenging, is the norm. Reinforcing this endemic bias for less onerous mitigation is the exclusion of uncertain carbon-cycle feedbacks anticipated, on average, to reduce available carbon budget space.

This ubiquitous preference for uncertainty that favours less onerous mitigation is dangerously weighting policy towards technocratic-only responses whilst at the same time closing down more challenging debates over lifestyles and deeper social-economic change. A measured approach would be to develop most scenarios with neither NETs nor positive carbon cycle feedbacks, with such uncertain parameters informing only the fringes of the analysis and providing the more extreme boundaries of possible scenarios.

2.1 IPCC carbon budgets

In November 2014, the Intergovernmental Panel on Climate Change (IPCC) published their Climate Change 2014 Synthesis report collating the findings of their three Fifth Assessment Reports (AR5). Bringing together expertise from across the IPCC's working groups, the Synthesis report provided a clear suite of "cumulative CO_2 emissions" (carbon budgets) for a range of different probabilities of "limiting warming" to below a rise of 1.5°C, 2°C and 3°C (relative to an 1861 to 1880 baseline).

These budgets are and will remain the subject of on-going and incremental refinement by climate scientists. However, until such time as a new consensus is arrived at the IPCC budgets remain the most authoritative source and should provide the foundation for any evidence-informed policies around energy issues related to climate change (see Table 2.2 of the IPCC Synthesis Report; copied below with the block arrows marking the most relevant rows to this report).

Table 2.2 | Cumulative carbon dioxide (CO_2) emission consistent with limiting warming to less than stated temperature limits at different levels of probability, based on different lines of evidence. *[WGI 12.5.4, WGIII 6]*

	Cumulative CO_2 emissions from 1870 in $GtCO_2$								
Net anthropogenic warming [a]	<1.5°C			<2°C			<3°C		
Fraction of simulations meeting goal [b]	66%	50%	33%	66%	50%	33%	66%	50%	33%
Complex models, RCP scenarios only [c]	2250	2250	2550	2900	3000	3300	4200	4500	4850
Simple model, WGIII scenarios [d]	No data	2300 to 2350	2400 to 2950	2550 to 3150	2900 to 3200	2950 to 3800	n.a. [e]	4150 to 5750	5250 to 6000
	Cumulative CO_2 emissions from 2011 in $GtCO_2$								
Complex models, RCP scenarios only [c]	400	550	850	1000	1300	1500	2400	2800	3250
Simple model, WGIII scenarios [d]	No data	550 to 600	600 to 1150	750 to 1400	1150 to 1400	1150 to 2050	n.a. [e]	2350 to 4000	3500 to 4250
Total fossil carbon available in 2011 [f]: 3670 to 7100 $GtCO_2$ (reserves) and 31300 to 50050 $GtCO_2$ (resources)									

The headline carbon budgets for the temperature ranges of below 1.5°C and 2°C (<1.5°C & <2°C in the row with the blue arrow) are the focus of this analysis. The row signalled with the yellow arrow provides the probabilities of staying below that temperature (for a more precise explanation of these probabilities see Notes b to e accompanying the Table 2.2 in the full IPPC report). The headline carbon budgets for each of these probabilities for 1.5°C and 2°C are provided in the row signalled with the green arrow. These cumulative budgets are calculated from a series of models assuming non-CO_2 forcing follows the RCP8.5 trajectory, close to current methane emissions rates, however similar values are found when other RCP scenario assumptions are used.

The carbon budgets are given in $GtCO_2$, i.e. billion (giga) tonnes of carbon dioxide. It is important to note the budget is for the period of 2011-2100; our analysis adjusts the carbon budgets to allow for emissions between 2011 through to and including 2017, with values for the period 2016 and 2017 extrapolated from near-term trends.[2]

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[2] *In preparing this report, confidential conversations were had with a small selection of climate scientists as to the appropriateness or otherwise of continuing to use the IPCC AR5 carbon budgets as the basis for analysis. Whilst there was universal agreement that these would ultimately need to be amended to account for evolving scientific understanding, at this time the budgets in the IPCC's Synthesis report remain apposite for the purpose of our analysis. An interesting facet of the discussions was an acknowledgement that the budgets were much less susceptible to*

2.2 The Paris Agreement

In December 2015, all 195 member states (including the EU) of the United Nations Framework on Conference on Climate Change (UNFCCC) adopted the final text of the Paris Agreement. One of the principal aims of the agreement is to hold "*the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*".

Another important commitment within the Paris Agreement and of particular relevance to this analysis is that "*Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties*". This explicit distinction between industrial and poorer and industrialising nations is important in determining how to apportion the global carbon budget between different nations.

2.3 Converting qualitative obligations into quantitative objectives

The language of various international agreements on climate change is typically framed in qualitative terms in relation to quantitative temperatures. The Copenhagen Accord is "*hold … below 2°C*"; the Camp David Declaration to "*limit… the increase … below 2°C*"; and now the Paris Agreement to stay "*well below 2°C*" – and importantly to "*pursue efforts to limit the temperature increase to 1.5°C*". In relation to all of these it would be disingenuous to suggest anything other than they require mitigation in line with at least a *likely* chance of remaining below 2°C. With its additional reference to pursuing efforts for 1.5°C, the Paris Agreement clearly implies a still more stringent likelihood, so at least a *very likely* chance of 2°C.

Within the IPCC's guidance notes to the authors of their latest report (https://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf), is provided a taxonomy of likelihoods that facilitate a translation of qualitative chances into quantitative probabilities. Based on "Table 1. Likelihood Scale" of the Guidance Notes the language of international agreements on climate change, from Copenhagen onwards, clearly relate to a 66-100% probability of not exceeding 2°C. The Paris Agreement, with its reference to pursing 1.5°C as well as 2°C, suggests a still higher chance of the latter – more in line with a 90-100% probability of not exceeding 2°C.

Table 1. Likelihood Scale	
Term*	**Likelihood of the Outcome**
Virtually certain	99-100% probability
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33 to 66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

"well below 2°C" ⟶ (Likely)

"pursue… 1.5°C" ⟶ (Unlikely)

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advances in scientific understanding than they were to potential changes in the assumptions about the levels through time of the non-CO$_2$ greenhouse gas emissions pathways.

Consequently, the sequential logic of the Paris Agreement leads to a carbon budget from IPCC's Synthesis report of somewhere between 850 and 1000 $GtCO_2$. The lower end of this range equates to an "unlikely" chance of staying below 1.5°C (i.e. a probability of 0 to 33% of <1.5°C) with the upper end relating to a "likely" chance of staying below 2°C (i.e. a probability of 66-100% of <2°C).

2.4   Estimating the global energy-only CO_2 budget post 2017

The 850 to 1000 $GtCO_2$ range is for all carbon dioxide emissions from all sectors for the period 2011 onwards. Therefore, in order to understand what emissions are available post-2017, it is necessary to subtract those emissions released between 2011 up to and including 2017. Based on Carbon Dioxide Information Analysis Center (CDIAC)[3] data, extrapolated to include 2017, at least 260 $GtCO_2$ will have been emitted since 2011; leaving a range of 590 to 740 $GtCO_2$ post-2017.

2.5   An allowance for CO_2 from deforestation & cement manufacture (process-CO_2 only)

Given this analysis relates specifically to the energy sector, it is necessary to remove projected global deforestation and industrial process (cumulative) emissions for the period post-2017; the latter of which relates primarily to cement production. It could be argued that these should both be considered at a national level, however, given the very clear equity steers within all agreements since the Copenhagen Accord, we argue that such emissions are more rightly considered as a global overhead. Wealthy industrial nations already have highly developed and cement-rich infrastructures – from the domestic and commercial built environments, to transport and energy networks, power stations and industrial facilities. Poorer and less-industrialised nations still have to construct their modern societies. Penalising them for their later development is inconsistent with the equity dimension of the various agreements. Similar arguments prevail for deforestation emissions, where most industrial nations have already benefitted from the land released through deforestation. Considering these emissions as a global overhead does not absolve those nations using cement and deforesting from responsibility. It does however reduce the burden and provide an incentive for all nations to encourage a global reduction in deforestation and the development of low-carbon cements (or alternatives).

Based on research recently published in Nature Geoscience (Anderson 2015), an optimistic interpretation of deforestation and cement process emissions post 2015 are, respectively, in the region of 60$GtCO_2$ and 150$GtCO_2$. However, for this analysis, still more optimistic assumptions have been made for both sectors, broadly in accordance with the considerable mitigation efforts required of the energy sector.

In terms of carbon dioxide from deforestation, and following on from the headline assumption #5, no reduction in the global carbon budget is made in this analysis. Given the high correlation between cumulative emissions across the century and temperature rise towards the end of the century, it is assumed here that enormous efforts are put into rapidly eliminating deforestation, with all related emissions more than compensated by a programme of afforestation and progressive changes in land-use. Under such an ambitious framework, the emissions from deforestation will occur earlier than sequestration from afforestation etc., consequently it is important that any planned programme of the latter is notably larger than the emissions of former. This is necessary to help reduce the very real risk that sequestration in the longer-term will not match emissions from deforestation in the nearer term.

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[3] CDIAC http://cdiac.ornl.gov/trends/emis/meth_reg.html

For this analysis two new cement scenarios have been developed using the most recent emissions data and with still more optimistic assumptions about the role of cement, and therefore process emissions, between now and the middle of the century. These scenarios are summarised in Box 2 and, for the purpose of this report, the highly optimistic estimate of process emissions from cement is assumed to be 100 $GtCO_2$ for the period post 2017.

Consequently, once allowance has been made for emissions from deforestation and cement, the global carbon budget range for energy-only emissions associated with the temperature commitments of the Paris Agreement reduces to between, approximately, 490 and 640 $GtCO_2$ (for post-2017). At current rates of emissions from energy, ~34 $GtCO_2$ per annum (CDIAC, 2016), this relates to between 14 years (for an "unlikely" chance of 1.5°C) and 18 years (for a "likely" chance of 2°C).

BOX 2: Global Cement Scenarios of Process Emissions (C1 & C2)

According to the Global Carbon Project's (GCP) emission database (*pers. comm.* Peters and Andrews, CICERO) cement process emissions grew at 5.5% p.a. between 1950 and 2015. Since 2000, the five-year annual average growth has been over 6% p.a., with the latest data for 2015-16 notably lower at just 2.4%.

There are almost no long-term forecasts or explicit scenarios of cement growth and emissions. However, the 2009 IEA Cement Road Map does provide two scenarios for cement growth from 2009 to 2050. That said the growth rates are far lower than those witnessed since 2009 or are evident over any period during the past six decades.

The two scenarios developed here (C1 and C2) both adopt the optimistic carbon intensity assumptions within the IEA report in relation to reducing the CO_2 emitted per tonne of cement produced. The IEA ratio of 60:40 for process relative to energy emissions is also maintained, but with CCS introduced to the industry by 2030 and increasing at different rates in C1 and C2 to complete (or very high) levels of penetration, and with complete or very high levels of capture, later in the century.

There is an evident anomaly between the (calculated) IEA and (published) GCP process emissions estimates for cement. Given this analysis relies on data from GCP (and CDIAC), a relatively small uplift factor is applied to the calculated IEA process emissions to bring the values into line with those from the GCP.

Both scenarios, C1 and C2, adopt growth rates that represent a step change from long-term historical trends, have growth rates that are maintained low through to 2030 after which they gradually decline still further. Of the two scenarios, C1 pushes the technology and growth reductions to levels that may have theoretical merit but are more difficult to justify as viable. In effect C1 risks implying that 'infrastructural development in poorer and industrialising nations is either significantly constrained or unknown alternatives to cement are discovered and penetrate the market from 2030 onwards. C2 is also highly optimistic, but with growth and technology not pushed to the limits assumed in C1. It is the C2 scenario that is adopted as appropriate for this analysis, demonstrating deep and profound mitigation, but with technologies just held back from their theoretical optimum.

C1: low cement growth, less than half that of historical trends, through to 2030, then reduces to growth of 1% p.a. by 2044 and no growth by 2054. CCS adoption begins in 2030 with CCS plants at 100% capture rate from the outset. Complete penetration by 2055 after which there are no emissions from cement production. Total post-2017 CO_2 of 69 $GtCO_2$.

C2: medium cement growth (still well below historical and recent rates), sees a gradual rise above from the latest (and anomalous) 2016 growth rate towards 60% of historical trend values. This is maintained until 2030 after which it falls to just 1% p.a. in 2055 and no growth from 2065. CCS starts in 2030, initially with 80% capture rate on the plants with CCS installed. This rate increases at 0.5 % p.a. to a maximum of 98% capture by 2066 after which it continues at that rate to 2100. Almost complete CCS penetration (i.e. 98% capture) occurs in 2061, with total post-2017 CO_2 of 100 $GtCO_2$.

2.6   Apportioning the global budget to industrial nations

This is undoubtedly an area where different interpretations of fairness and equity can give potentially very different results in terms of national carbon budgets. However, the Paris Agreement (and its UNFCCC forebears) all draw attention to the importance of issues of equity and how poorer and less industrialised nations (hereafter referred to as industrialising nations) will need some significant period of grace in terms of decarbonising their energy systems. Specifically, they acknowledge that the

peak in emissions from these poorer nations will be later than that within the wealthier industrial nations (hereafter referred to as industrial nations). Combine this equity criterion with the small and rapidly dwindling global carbon budget for 2°C (i.e. 490 to 640 $GtCO_2$) and the range of potential national budgets is very significantly constrained.

The approach adopted here builds on the pragmatic and open process of apportionment used in Anderson & Bows (2011). Put simply, the approach recognises the highly constrained nature of the 2°C carbon budget and then asks, within such a constraint, what is the most ambitious peak date industrialising nations could achieve and what could they subsequently deliver in terms of mitigation rates. This permits a mitigation pathway to be plotted for these nations. It is worth noting here, that the emission profile of China dominates those of the industrialising nations. Furthermore, even at a per-capita level, China is undoubtedly wealthier than many of the so-called "developing" nations. Consequently, an emission profile for industrialising nations will mask the fact that many poorer nations will have a peak in their emissions up to a decade after that of China.

For this report, a series of updated scenarios (Box 3) have been generated, building on earlier research (Anderson & Bows, 2011) and recognising the stipulation of the Paris Agreement that industrialising nations will take longer to make the transition away from fossil fuels than richer more industrialised nations. For the analysis here, industrialising and less developed nations are captured within the non-OECD classification; in relation to emissions, this is sufficiently close to both non-Annex 1 and non-Annex B groupings to make no discernible difference.

The non-OECD scenarios developed for this report assume highly ambitious rates of mitigation beyond any thus far considered in other similar analysis. Nevertheless, the cumulative emissions for even these early and deep mitigation scenarios have fundamental implications for both the Paris temperature commitments and the 2°C mitigation challenge of the industrialised/OECD countries.

The post-2017 cumulative emissions for the non-OECD region range from:

S1: 2020 peak emission year; 10%p.a. mitigation by 2042; 95% CO_2 cut by 2060 = **502GtCO$_2$**

S6: 2025 peak emission year; 10%p.a. mitigation by 2047; 95% CO_2 cut by 2065 = **620GtCO$_2$**

What is immediately evident, is that even a highly ambitious mitigation programme by the non-OECD region would have cumulative emissions in excess of the fossil-fuel carbon budget for an "unlikely" chance of staying below 1.5°C (i.e. 490 $GtCO_2$). Consequently, from a carbon budget and mitigation perspective, 1.5°C is no-longer a viable temperature commitment.

Moreover, a mitigation agenda across the industrialising nations at a level of ambition far beyond anything discussed in Paris would also exceed the global (energy-only) carbon budget for a "very likely" chance of 2°C. That is to say, a strict reading of the political framing of the Paris ambition in terms of "well below 2°C" is also now not a viable goal. For the more conservative reading of Paris underpinning this report, the carbon budget accompanying a "likely" chance of 2°C remains viable - just. However, the enormous scale of ambition embedded in the non-OECD scenarios still delivers emissions that consume between 78% and 98% of the remaining fossil fuel global carbon budget.

BOX 3: Non-OECD emission scenarios

The six non-OECD scenarios (S1 to S6) generated for this report are all for fossil fuels only, are highly ambitious and beyond anything thus far countenanced in international negotiations or in existing scenario sets. Process and deforestation (LULUCF) CO_2 have been subtracted from the GCP database using estimates provided through personal communication with the GCP team who compile the data.

The scenarios include emissions data of the respective bunker fuel emissions from international aviation and shipping. These values are based on the difference between GCP *global* emissions and the sum of OECD and non-OECD emissions (a difference of approximately 4%). According to personal communication with the GCP team this difference accounts for emissions from bunker fuels. For the analysis here, bunker fuel emissions are split between non-OECD and OECD on the basis of the regions' relative proportion of global emissions (excluding bunkers). Following this approach (i.e. excluding CO_2 from industrial processes & LULUCF, but including bunkers), the non-OECD and OECD emissions in 2015 were, respectively, 21.3 $GtCO_2$ and 13.0 $GtCO_2$.

Beginning from the 2015 emissions level, all scenarios initially grow at the same non-OECD rate as occurred in the years for which the latest data is available, i.e. 2014-15, where growth was 0.4%. This rate is far lower than historical rates for the region, but is considered appropriate here as this analysis is premised on immediate and unprecedented global effort to mitigate emissions in line with the Paris temperature commitments and the associated IPCC AR5 carbon budgets. *[The authors acknowledge that action at this scale is highly unlikely in the near-term and that, as yet, there is no suggestion that such mitigation will be forthcoming in the medium-term*].
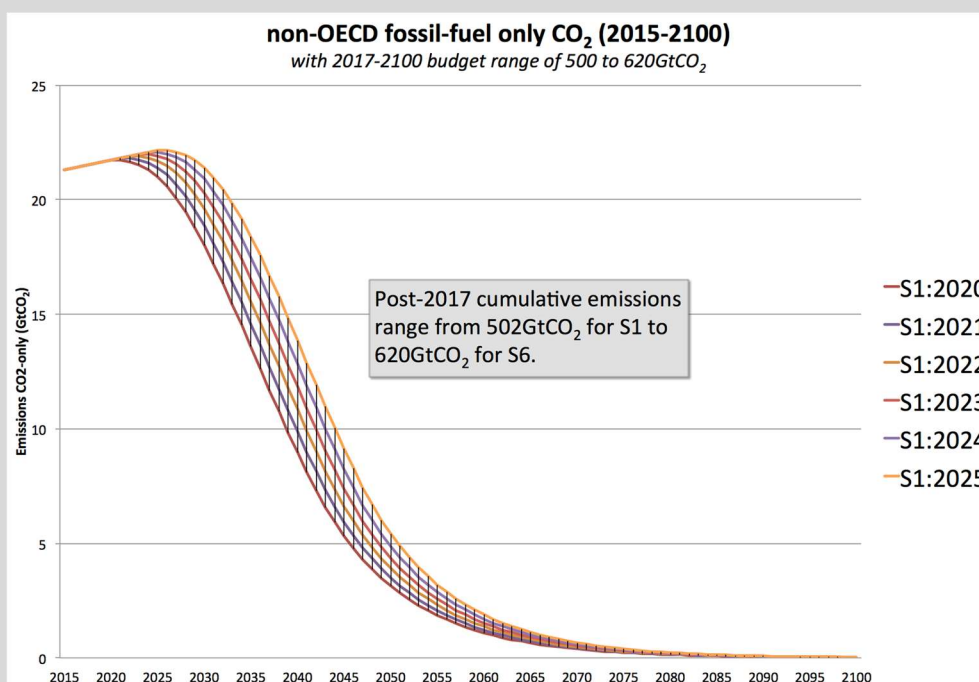
Figure 2 Emissions pathways for non-OECD countries for a range of peaking dates.

The year when emissions peak varies across the six scenarios, from 2020 for S1 through to 2025 for S6. Once at peak emissions, all scenarios roll over to begin mitigation at 0.1% in the first post-peak year rising to a 1% reduction four years later before increasing at 0.5% each year to a maximum of 10% p.a.; this occurs 22 years after the peak year. Mitigation efforts thereafter deliver 10% reductions in absolute emissions each year for the remainder of the century. All the scenarios deliver an absolute reduction in emissions of approximately 95% (c.f. 2015) by 2060 to 2065 respectively. The total post-2017 cumulative emissions for the scenarios range from a low of 502 $GtCO_2$ for a non-OECD peak in 2020, through to 620 $GtCO_2$ for a peak in 2025.

2.7   What carbon budget remains for the nations of the OECD?

The previous sub-section demonstrated that the Paris requirement of nations "*to pursue efforts to limit the temperature increase to 1.5°C*" is no longer a viable mitigation commitment. Furthermore, a "*very likely*" chance of staying "*well below 2°C*" is also now beyond any conceivable mitigation programme. However, holding emissions within the carbon budget range for a "*likely*" chance of 2°C does, at least theoretically, remain achievable. It is this agenda that now provides the focus of the remaining analysis within this "carbon budget" section.

With a global energy-only CO_2 budget of 490 to 640 $GtCO_2$ (from 2017), and with non-OECD cumulative emissions (according to scenarios S1 to S6) of 502 to 620 GtCO2, the remaining budget range for the OECD extends from a high of 140 $GtCO_2$ to a low of just 20 $GtCO_2$. Transposing these into theoretical mitigation rates, these equate to immediate and prolonged cuts in emissions of between 9% and 40% p.a.

2.8   What carbon budget for the EU (for a fair contribution to a "likely" chance of 2°C)?

There are various regimes for apportioning the emissions budget from the industrialised nations grouping of the OECD to individual nations or regions. Such approaches cover relatively simple population or grandfathering (allocation on the basis of recent emissions) to more elaborate relationships founded on economic wherewithal, geographic and cultural capacity etc. For this report, and given that the EU is anyway geographically, culturally, technically, politically and economically diverse, three basic apportionment regimes are used to attribute a "fair" budget to the EU: grandfathering, GDP and population.[4] Such a straightforward approach is further justified as in terms of equity, measured here simply as GDP/capita, the EU and OECD are very similar (typically within 6% of each other[5]). If a subsequent level of apportionment was required to disaggregate an EU carbon budget to disparate member states, more sophisticated regimes would, arguably, need to be considered.

Based on EU and OECD data from 2010 up to and including 2015, the three apportionment regimes adopted for this project allocate to the EU 28% (Grandfathering), 37% (GDP) and 40% (Population) of the OECD's post-2017 energy-only CO_2 budget range (140 to 20 $GtCO_2$). Building on this the EU's post-2017 budget range is outlined in Table 1, below, with the final (red) column providing central budget range for this report.

What is immediately obvious from Table 1 is how sensitive the EU's carbon budget is to the precise date when the emissions of the non-OECD nations reach a collective peak in emissions (see footnotes). The choice of apportionment regime, at least for those applied in this report, has only a relatively small impact on the size of the EU's budget.

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[4] Grandfathering here relates to apportioning the OECD carbon budget to the EU based on the ratio of the EU's recent annual emissions to those of the OECD. The proportion used is the mean of the EU:OECD ratios for the years 2010 to 2015.

[5] Based on OECD and EU data for each year from 2010 to 2015 inclusive.

Table 1 EU "likely" 2°C post-2017 energy-only CO_2 budget (GtCO_2)

Apportionment regime	OECD upper value (140 GtCO_2) [6]	OECD lower value (20 GtCO_2) [7]	EU mid-value CO_2 budget[8]
Grandfathering (28% of OECD)	40	6	23
GDP (37% of OECD)	51	7	29
Population (40% of OECD)	56	8	32

2.9   What rate of mitigation rate for the EU to meet its 2°C commitments?

The purpose of this report is to assess the viability or otherwise of an expansion of gas as a fuel source within an EU energy programme intended to deliver on the EU's Paris commitments. It has already been established that despite very stringent criteria it is no longer possible for the global community to mitigate energy emissions in line with the carbon budget range for even an "unlikely" chance of 1.5°C. In relation to the budgets for a "likely" chance of 2°C, a small but rapidly dwindling prospect remains, with the EU's respective carbon budgets outlined in Table 1. Translating these budgets into simple mitigation pathways, and hence rates, provides a quantitative framework within which new, (or indeed, existing) gas supply would need to fit.

To provide a top-level mitigation pathway, the budgets summarised in Table 1 are transposed into stylised mitigation pathways for the EU. These pathways assume a post-2107 mitigation rate reducing emissions at a sufficient rate to maintain total emissions within the given budgets. As such, the rates of mitigation necessarily underplay the actual rates that would be required once allowance is made to transition from the EU's current and very gradual mitigation to a rate tuned to deliver the respective carbon budgets. Table 2, below, summarises the findings of this mitigation analysis.

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[6] Assumes a peak in non-OECD emissions by 2021.
[7] Assumes a peak in non-OECD emissions by 2025.
[8] Assumes a peak in non-OECD emissions between 2022 and 2023. To remove any spurious precision, this is rounded to between 20 and 35GtCO_2 in the "key messages" text.

Table 2 EU "likely" 2°C post-2017 energy-only CO_2 mitigation rates.[9]

Apportionment regime		Based on OECD upper value (140 $GtCO_2$)[10]	Based on OECD lower value (20$GtCO_2$)[11]	Based on mid-value CO_2 budget [12]
Grandfathering	**(28%)**	9%	60%	**16%**
GDP	**(37%)**	7%	50%	**12.5%**
Population	**(40%)**	6.5%	45%	**11.5%**

An immediate issue with the mitigation rates described in Table 2, is the inequitable position that arises when the EU's mitigation agenda depends on highly ambitious non-OECD scenarios (e.g. S1 to S6). Under such circumstances, the EU mitigation rate is lower than that ultimately demanded of the non-OECD nations. Given the substantial (and growing) asymmetry for existing anthropogenic climate change between wealthier and poorer/industrialising nations, it would be difficult, if not impossible, to justify lower mitigation rates for the EU than those finally required by non-OECD nations, even though there is an important time differential between the two. For this reason, the headline recommendation of this report, in relation to the EU, is that its immediate mitigation rate be at a minimum of 12% p.a. and ideally at 16% or higher. Any delay in delivering on such mitigation will rapidly see either the rate increase still further, or the EU's relative inaction jeopardise global delivery of the Paris 2°C commitment. This issue is outlined in the Appendix, where illustrative EU emission pathways for the mid-value carbon budgets in Table 1 are presented.

2.10 What quantities of natural gas could be consumed whilst fitting within these budgets?

The carbon budgets outlined above can be converted to an equivalent volume of natural gas that would give such emissions when combusted.[13] Considering only the CO_2 arising from combustion, the entire carbon budget would be exceeded in 28 to 39 years at current rates of EU gas consumption. That is without *any* oil or coal being burned in, for instance, road transport, aviation, shipping or power generation or allowance for any supply chain emissions outside the EU.

For context, global natural gas production is approximately 3500 bcm per annum and EU consumption is 400 bcm (BP, 2016). Current proved reserves for Norway, Netherlands and UK combined are 2800 bcm, for Russia 32300 bcm and globally 186900 bcm.

In Table 3 below, in blue, CO_2 budgets and equivalent quantities of natural gas implied by the current EU NDC and long-term targets are also included for comparison. An assumption is made that all energy emissions arise from unmitigated natural gas combustion, either immediately in 2017 or with a phase out of coal and oil over 5 and 10 years respectively. These trajectories assume that all sources of emissions are

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[9] The 2017 starting value of EU CO_2 emissions from energy is based on the GCP 2015 data with bunker fuel emissions added and cement removed (for simplicity, both are based on the OECD values for these emissions sources adjusted to the EU on the basis of the EU's fraction of total OECD 2010 to 2015 population (i.e. 40%). The 2017 value is a straightforward extrapolation of recent EU CO_2-only emissions trends.

[10] Assumes a peak in non-OECD emissions by 2021.

[11] Assumes a peak in non-OECD emissions by 2025.

[12] Assumes a peak in non-OECD emissions between 2022 and 2023.

[13] Relevant constants are detailed in Section 4.2.5

reduced in equal proportion to 2050. This assumption is unlikely to hold, as non-energy sector emissions (e.g. from agriculture) are likely to be more difficult to reduce.

Table 3 Equivalent quantities of gas consumption for "likely" 2°C carbon budgets and NDC

Apportionment regime		EU mid-value CO_2 budget (GTCO₂) [14]	Equivalent quantity of natural gas (bcm)	Equivalent years at current rate of EU gas consumption	Proportion of global proved reserves
Grandfathering		23	11000	**28**	6.0%
GDP		29	14000	**35**	7.6%
Population		32	16000	**39**	8.4%
NDC then 80% 2050 target	All gas from 2017	74	36000	**90**	19%
	Coal phase out 2022 Oil phase out 2027		32000	**80**	17%
NDC then 95% 2050 target	All gas from 2017	67	33000	**82**	18%
	Coal phase out 2022 Oil phase out 2027		29000	**72**	16%

2.11 Fossil fuels have no substantial role in an EU 2°C energy system beyond 2035.

Building on the IPCC's carbon budgets, the apportionment regimes discussed in Section 2 are associated with a minimum reduction in EU energy-only carbon emissions of around 95% by 2035 (c.f. 2015). Such a programme of mitigation, similarly played out at a global level, requires significantly more than two thirds of existing reserves to remain in the ground (McGlade and Ekins, 2015).[15] Consequently, in delivering a mitigation programme for 2°C, there is categorically no role for bringing additional fossil fuel reserves, including gas, into production. This conclusion is not significantly affected by the prospect of carbon capture and storage. Limitations on deployment rates and likely upstream methane emissions substantially restrict the potential of CCS (Gibon, 2017; Cuéllar-Franca and Azapagic, 2015), even with a conservative reading of the Paris 2°C commitment, a rejection of 1.5°C and a weak interpretation of equity. An urgent programme to phase out existing natural gas and other fossil fuel use across the EU is an imperative of any scientifically informed and equity-based policies designed to deliver on the Paris Agreement.

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[14] Assumes a peak in non-OECD emissions between 2022 and 2023. To remove any spurious precision, this is rounded to between 20 and 35GtCO₂ in the "key messages" text.

[15] This estimate from McGlade and Ekins assumes a 50% chance of 2°C rather than the 66-100% chance used in this analysis. Moreover, their analysis relies on the significant and successful uptake of negative emission technologies. Both of these permit a much greater use of fossil fuels than is implied in the Paris Agreement.

3 The climate change impact of methane

There are a range of natural and human processes that alter the energy balance of the atmosphere and oceans causing the climate to change. The main human activity responsible for climate change is the release of greenhouse gases (GHGs), of which carbon dioxide (CO_2) is the most significant and the focus of the preceding section. However, non-CO_2 GHGs have accounted for about 25% of anthropogenic emissions since 1970 (IPCC 2014 AR5 Synthesis Report) and will have a meaningful influence on future climate change. Methane is by far the most important of these, and its atmospheric concentration has more than doubled since pre-industrial times as a result of emissions from a wide range of natural and human sources (Saunois et al, 2016). Each molecule of methane has a stronger warming effect than carbon dioxide although a much shorter atmospheric lifetime of the order of a decade rather than centuries. However, almost all methane released into the atmosphere is ultimately oxidised to CO_2, and hence the warming effect is always greater than CO_2 for the same amount released.

This section considers the climate change impact of methane, distinct from carbon dioxide. It examines current trends in atmospheric concentration and emissions from various sources. It considers aggregate emissions at a coarse scale; it does not focus on the natural gas industry, specific supply chains or particular regions, these emissions are considered later in Section 4. Section 4 also goes on to consider how methane should properly be accounted for in climate policy, specifically in terms of relative metrics to compare the impact of different gases. This is necessary background to review the quantities of emissions associated with different parts of Europe's natural gas supply chains within Section 4.

3.1 Trends in atmospheric methane concentration and methane emissions

Methane has become the focus of increased attention due to a sharp rise in atmospheric concentrations in recent years. Reviews of multiple sources suggest that the concentration reached a plateau in the early 2000s (+0.5 ± 3.1ppb yr^{-1}) but has subsequently returned to growth at +6.9 ± 2.7 ppb yr^{-1}, (Saunois 2016; Dlugokencky 2016). 2014 and 2015 saw even higher rates of increase at 12.5 and 9.9 ppb yr^{-1} respectively. These rates and observed concentrations are at the upper end of the scenarios used by the IPCC to anticipate future climate impacts, greater than RCP 2.6, 4.5 and 6 (see Figure 3), and beyond any changes identified in the last 1000 years of ice core records (Nisbet et al 2016).
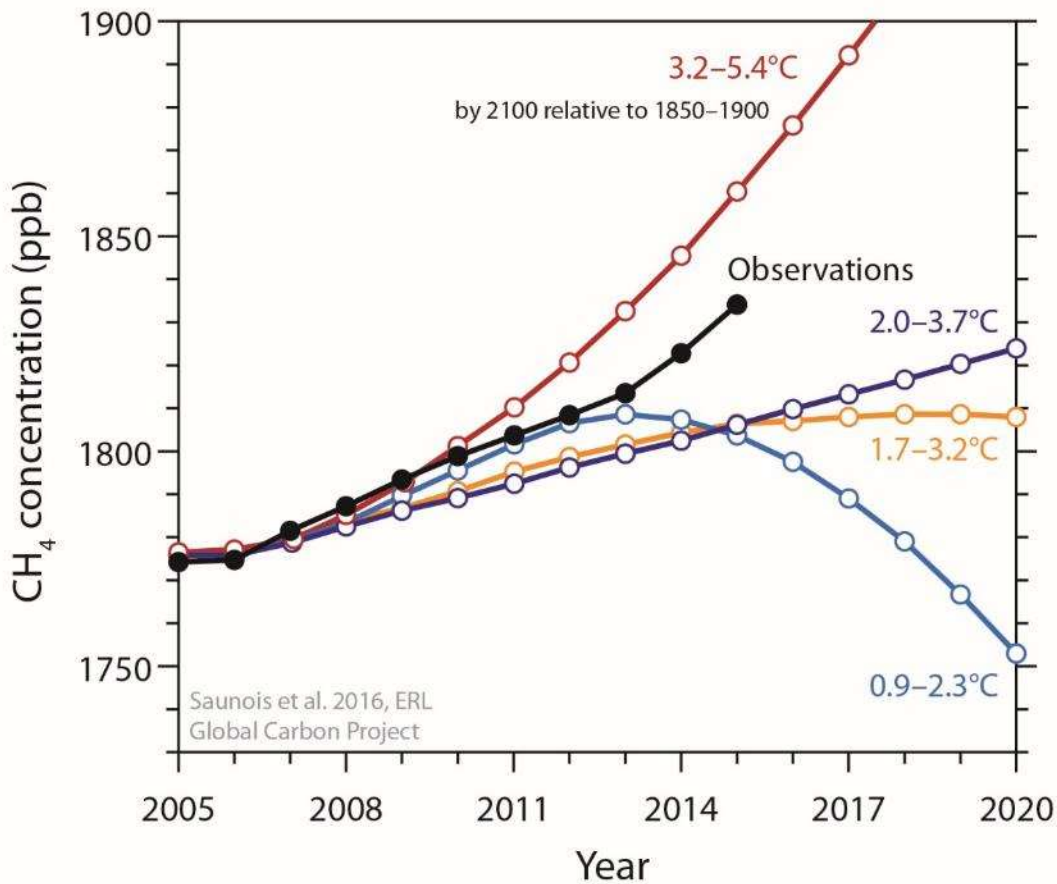
Figure 3 Observed methane concentrations in comparison to IPCC scenarios. Source: Saunois et al 2016, Global Carbon Project

Whilst it is clear that methane concentrations in the atmosphere are rising there remains uncertainty as to why that is the case. Multiple mechanisms contribute to the accumulation of methane and their relative influence in explaining observed patterns is disputed. There is substantial uncertainty in the proportion of natural and anthropogenic sources, the impact of changes in regional weather conditions, the extent of biological feedbacks, and in trends in the most significant removal mechanism, the hydroxyl (OH) radical (Dalsoren et al 2016). There are also trends in regional sources to consider, for instance time series measurements from surface and satellite observations suggest that the USA alone could be responsible for 30 to 60% of the global increase from 2005 to 2010. Section 4.4 discusses these studies in more detail.

Methane originates in biogenic (biological), thermogenic (geological) and pyrogenic (combustion) processes and reaches the atmosphere as a result of diverse natural or human activity (see Table 4). These sources are often not isolated geographically so distinguishing them once in the atmosphere is challenging. There is also overlap between categories with a proportion of fossil fuel methane, notably from shales and coal seams, having a biogenic origin (Colosimo et al 2016). Likewise, the methane released from thawing hydrates (terrestrial and marine), can have both thermogenic and biogenic origins.

Table 4 Origins of atmospheric methane

	Release to the atmosphere	
Generating process	*Natural*	*Human made*
Biogenic	Wetlands, lakes, rivers, permafrost, termites, oceanic sediment, methane hydrates	Agriculture, particularly rice and ruminant livestock (sheep, cows), waste, landfill, fossil fuels (minor component)
Thermogenic	Geological seeps, volcanoes, methane hydrates	Fossil fuel production and combustion (major component)
Pyrogenic	Wild fires	Biomass combustion

The Global Carbon Project (http://www.globalcarbonproject.org/) has recently brought together current knowledge on the flows of methane to and from the atmosphere in a global methane budget. The exercise considers atmospheric concentrations and sinks and uses two approaches to estimate sources of emissions; top-down and bottom-up.

The total quantity of emissions to the atmosphere is constrained by concentration measurements and estimates of the lifetime of methane in the atmosphere. Top-down accounting methods start with these atmospheric measurements and work back to sources using models of atmospheric transport, chemical processes and a priori assumptions about source locations, isotopic ratios (the atomic "fingerprints" of sources), and emissions rate constraints. Satellite measurements offer global top-down coverage but due to relatively low instrument precision require repeated measurements, over a period of months to years, to determine accurate values (Turner et al 2015). Conversely, bottom-up inventories start by measuring the rate of emissions from known sources and scale these to a total quantity using data on the extent of such sources, such as the number of operating oil and gas facilities, or the area under a given agricultural regime. As such data are often gathered annually for other socio-economic purposes, higher temporal resolution is possible than global top down estimates. For instance, Figure 4 illustrates recent trends in anthropogenic methane from inventory studies in comparison to the IPCC scenarios, with all at the upper end of emissions paths. Inverse methods are some way between these approaches, using mathematical models to identify the most plausible allocation of atmospheric measurements to sources given some initial (prior) information on the distribution of sources and constraints on their possible ranges.
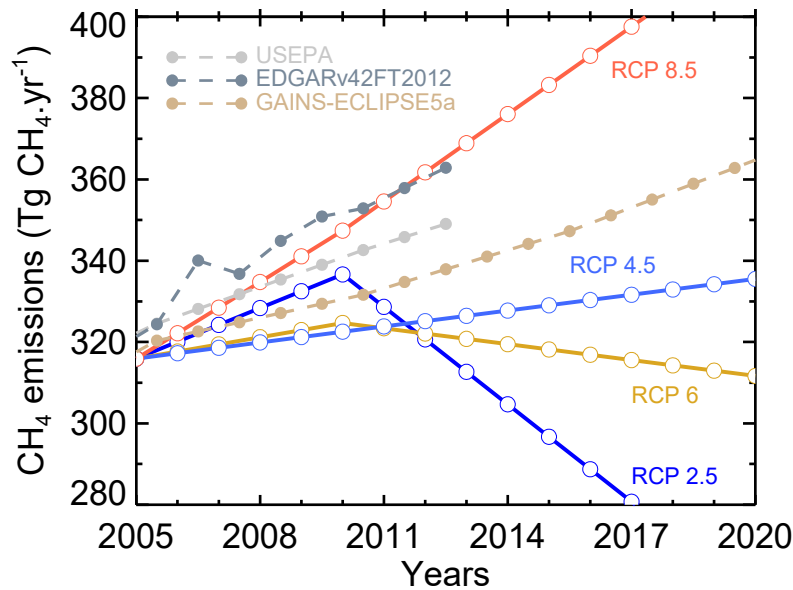
Figure 4 Anthropogenic methane emissions estimated by three bottom up inventories, compared to IPCC scenarios. The Global Methane Budget top-down estimate for 2012 is comparable to the RCP 8.5 path at 347 Tg/yr. Variation in emissions from coal mining explain most of the difference between the bottom up inventories; the emissions factors used in EDGAR for China, a major producer, may be an overestimate by a factor of 2. Source: Saunois et al 2016, Global Carbon Project

The most recent comprehensive top-down estimate, using an ensemble of eight three-dimensional inversion models, that divide emissions between sources according to regional measurements and models of weather and chemistry, reports total emissions of 568 (min 542, max 582) Tg methane/yr for 2012, of which 347 (min 262, max 384) Tg is estimated to arise from all anthropogenic sources (Saunois et al 2016). Bottom up inventories report substantially higher global emissions than top-down estimates, which Saunois et al (2016) record at 756 (min 609, max 916) Tg methane/yr[16] for 2012, of which 370 (min 351, max 385) Tg is estimated from anthropogenic sources. Previous global emissions estimates are within these ranges; Turner et al (2015) report total global emissions of 539 Tg/yr of which 358 Tg/yr is identified as anthropogenic (top-down method, for period 2009-2011), Kirschke et al (2013) report 548 (min 526, max 569) Tg/yr of which 335 (min 273, max 409) is anthropogenic for the decade 2000-2009 using top down methods and 678 (min 542, max 852) of which 331 (min 304, max 368) is anthropogenic using bottom up methods. Saunois et al (2016b) argue that whilst there is no consensus in attribution to sources from top-down studies, they are nonetheless better constrained by observation than bottom-up estimates at the global level. These estimates therefore place anthropogenic methane emissions at the upper end of IPCC scenarios, closer to RCP 8.5 than the various mitigation scenarios.

3.2   Attribution of recent atmospheric increases

The recent, post 2006, rise in atmospheric methane concentrations must be explained in terms of changes in quantities of emissions or sinks. Sinks are processes that reduce the quantity of methane in the atmosphere and affect the atmospheric concentration; as such a rise could be explained by a weakening sink as well as by increasing emissions. The dominant sink, representing approximately 90% of methane removal, is oxidation to CO_2 by the hydroxyl (OH) and other radicals in the atmosphere (Kirschke et al 2013). Although the photochemical processes that govern the OH sink are well understood, the spatial and temporal distribution

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[16] One teragram (Tg) is 10^{12} grams, equivalent to one million tonnes.

of OH radicals is difficult to characterise because of their very short atmospheric lifetime (of the order of 1 second). There is good evidence to suggest that the sink has strengthened and the lifetime of methane in the atmosphere has reduced since the 1970s (Dalsoren et al 2016). A shorter methane lifetime would tend to reduce atmospheric concentrations of methane; however, this may have changed in recent years in the opposite direction. Turner et al (2017) have argued that current observations are ambiguous as to whether it is emissions growth or reductions in hydroxyl radical concentration that has led to the post-2006 increase in methane concentrations. The authors of this latter study do however point out that their model is based on hemispheric aggregation, and models at lower spatial scale and higher temporal frequency suggest that variation in the OH sink does not explain observed patterns in isotopic ratios and short-term changes (Nisbet et al 2016). Nisbet et al (2016) instead conclude that emissions growth, dominated by biological sources in tropical wetlands and agriculture, best explains recent atmospheric observations.

3.3   Trends in aggregate methane emissions due to fossil fuels

Considering absolute fossil fuel emissions global estimates conflict as to recent trends. Kirschke et al (2013) review decadal averages for 1980s, 1990s and 2000s, and report this source of emissions as constant from top down estimates (1990s min-central-max: 84-95-107 Tg/yr, 2000s range: 77-96-123 Tg/yr), although with low agreement between studies, or increasing slightly from bottom up studies where there is better agreement (1990s min-central-max: 66-84-96 Tg/yr, 2000s range: 85-96-105 Tg/yr). The authors also note that there are multiple combinations of trends in sources for the stabilisation of atmospheric concentrations and that allocation to sectors or through time was not well constrained. Updated estimates for 2012, presented in Saunois et al (2016), suggest a rise in fossil fuel sources to 90-112-137 Tg/yr (top down) or 123-134-141 Tg/yr (bottom up).

Molecules such as ethane and propane, that have common origins and are released simultaneously, can provide an indicative marker. Atmospheric ethane concentrations have been observed to decline in a global monitoring data set from 1984 to 2010 and this has been attributed to reduced venting from oil and gas facilities after accounting for increasing biofuel and biomass burning (Simpson et al 2012). The authors conclude, indirectly, that this was accompanied by a similar reduction in associated methane releases, the extent depending on the methane:ethane ratio (MER) adopted. A more recent study drawing on data from two sites shows a reversal in this trend in the Northern Hemisphere, with an increase observed from 2007 onwards. Using a simple two box model and a range of MER scenarios, Hausmann et al (2016) propose that between 18% and 73% of the increase in atmospheric methane contributions could be associated with oil and gas production. Further data from a global network of atmospheric monitoring, reported in Helmig et al (2016), also shows an increase in ethane emissions beyond 2010 with a spatial distribution congruent with US oil and gas production. However, the quantities of ethane identified in these studies would suggest a much larger increase in regional methane emissions (4.4 ± 3.1 Tg/yr), more than doubling the US EPA inventory. They are also much larger than many of the site and regional studies detailed in Appendix B, Table 10 and Table 11, if it is assumed that all of the ethane increase is indeed from fossil fuel sources and the MER has not changed through time. Variability in gas composition between reservoirs limits the precision of this technique for attributing quantities of methane emissions nor can it distinguish natural seepage from industrial activity without local measurement (e.g. Smith et al 2017). Natural gas from some oil rich reservoirs, such as the Bakken shale, North Dakota USA, contains a much greater proportion of these longer chain hydrocarbons than other sources. Through airborne sampling over this region in 2014, Kort et al (2016) note that the recent and very substantial growth in the shale gas and oil industry in this area has led to ethane emissions since 2010 that could bias global estimates of methane emissions if a constant MER was assumed through time.

Carbon and hydrogen isotope ratios provide an indication of the process that generated that methane and ethane and therefore point to the likely source (Schwietzke et al 2016). Rice et al (2016) infer from a long-term record of atmospheric isotope ratios that methane emissions from fossil fuel production are likely to have increased by 24 Tg/yr from 1984 to 2009, and that changes in biomass burning better account for ethane reductions than reductions in fossil fuel fugitive emissions. Conversely, using the largest database of its kind, Schwietzke et al (2016) conclude from isotopic signatures that, globally, methane emissions from all fossil fuels did not increase from 1985 to 2013, although the absolute quantity of emissions was underestimated by 20% to 60% relative to the US EPA and the EC EDGAR inventories. This corresponds to total fossil fuel emissions of 195 ± 32 Tg/yr (1 standard deviation) in 2013 of which 145 ± 23 Tg/yr is attributed to fossil fuel industries and 51 ± 20 Tg/yr to geological seepage. Importantly, they documented the statistical uncertainty associated with the isotopic measurements and use this to constrain allocations to sources. This dataset also suggests that the proportion of methane leaking to the atmosphere from the natural gas industry has reduced since the mid-1980s, from approximately 8% to 2%, when increasing production is accounted for. Note that this methane leakage rate is expressed as the proportion of methane emissions from all fossil fuel sources, as a proportion of natural gas production, so is not directly comparable to studies focussing on gas only.

Other work has also argued that the isotopic signature accompanying the post-2006 increase in atmospheric methane is predominantly associated with tropical biogenic sources, most likely agriculture related (Nisbet et al 2016, Schaefer et al 2016). Whilst these studies determined that absolute increases in emissions from the fossil fuel industry could not be ruled out they were not likely to dominate recent increases. Like Schwietzke et al (2016), findings from recent field studies in the US, reviewed in detail in Section 4, frequently identify existing inventory data to be an underestimate of measured emissions. Given the wide uncertainty ranges in global estimates, it is also plausible that there have been post-2006 increases in absolute fossil fuel emissions, coincident with more rapid growth in non-fossil fuel sources. Further empirical research, including field studies in other regions, will clarify these issues.

As summarised in Figure 5 below, the Global Methane Budget review (Saunois et al, 2016b) concludes that at the global level there is reasonable agreement between approaches for wetland and agricultural sources, despite large ranges. There is a particular difference between top down and bottom up approaches in the estimation of "other natural" source categories which excludes wetlands but includes *inter alia* freshwaters, wild fires, termites and permafrost. This category represents 27% of global total emissions for the latest bottom up data (Saunois et al 2016). No significant contribution from Arctic regions, as has been proposed due to warming permafrost, has yet been identified, however, seepage from geological features, both natural and potentially induced by fossil fuel production, is also part of this category with large uncertainties (±50%) due to limited field sampling. The global top-down estimates of fossil fuels and other natural sources are generally lower than current bottom up estimates, although they may be biased by erroneous emissions factors for coal production. This contrasts with the Schwietzke et al (2016) revision substantially upwards using a top down method. In sum, combined natural seepage and anthropogenic emissions are found by bottom up estimates to be ~30% of total global emissions which is consistent with isotopic analysis (Saunois et al 2016).
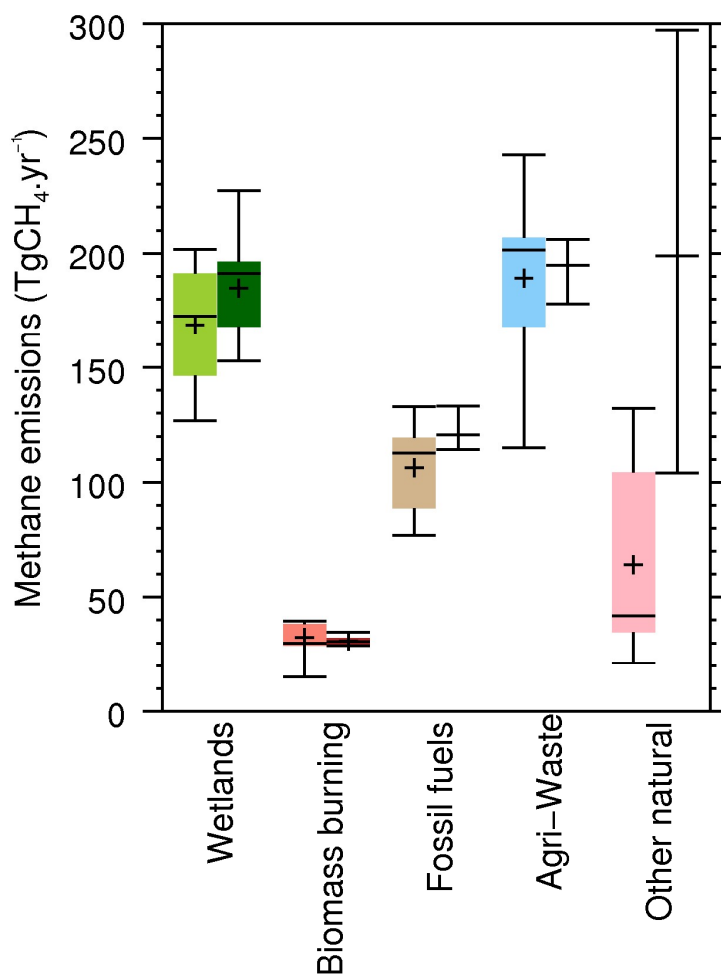
Figure 5 Global methane budget estimates of sources of emissions 2003 to 2012, top-down estimates on the left, bottom-up estimates on the right. Ranges are given as min-max and interquartile range for studies. Source: Saunois et al 2016

3.4   Conclusion

At present, more than half of total methane emissions are considered to be anthropogenic, and approximately a third of these are associated with fossil fuels. Atmospheric concentrations of methane are at the upper end of IPCC scenario pathways, with a clear signal of a sustained rise since 2006. Attribution of this growth to sources is as yet inconclusive although i) there is isotopic evidence that the post-2006 rise in atmospheric concentrations is predominantly due to growth in tropical biogenic emissions, whilst ii) regional measurements of emissions suggest that bottom-up inventories of US oil and gas emissions are an underestimate of actual emissions and that these local sources are increasing, and iii) that reductions in the OH sink has been suggested as also contributing to the net increase since 2006. However, there is not yet scientific consensus on these conclusions (Allen, 2016) and it is hoped that further empirical research, and ongoing review through the Global Methane Budget, project will constrain the ranges of these estimates and lead to greater confidence in future. Section 4 considers site and region-specific measurement studies in more depth in relation to allocating emissions to natural gas supply chains.

4 Greenhouse gas emissions from the natural gas supply chain

Natural gas is predominantly composed of methane so leakage and deliberate venting contribute to climate change over and above the carbon dioxide produced by its combustion. Following the rapid growth in US natural gas production from shale plays and other unconventional reservoirs, there has been substantial interest in the potential for a natural gas to act as a "bridge" in climate and energy policy. The potential for methane emissions to undermine the benefits of switching to gas, in terms of reduced carbon intensity relative to coal, coincident with the resumption of rising atmospheric concentrations of methane, has led to considerable research interest in the quantities, locations and variability of methane emissions arising from the natural gas industry. However, the bulk of this work has focussed on the US natural gas system, with limited recent empirical research elsewhere in the world. This section provides an overview of the work available and assesses the relevance for EU policy making. It begins by considering the metrics that are required to enable a meaningful comparison of different supply chains.

4.1 Comparing Greenhouse Gases

The full range of climate forcing agents includes well mixed greenhouse gases (WMGHGs) such as carbon dioxide, methane and nitrous oxide, in addition to other pollutants such as sulphate aerosols, black carbon particles and aircraft induced cloudiness. The term Short Lived Climate Pollutant (SLCP) is used to distinguish agents with short term impacts, a decade or less, some which may also have geographically specific effects because they are not well mixed. Each agent causes cooling or warming in different ways, directly by altering the atmosphere's energy balance, and indirectly by altering other chemical or physical processes. The various climate forcing agents also have different lifetimes so volumes, masses or amounts cannot simply be summed to compare to their warming effect through time.

Figure 6 illustrates these differences highlighting the greater short-term warming caused by methane (blue line) in comparison to longer term warming due to CO_2 (red line). 10 years after the pulse of emission the methane has caused a temperature change three times greater than the CO_2 although it tends to very little by 100 years.
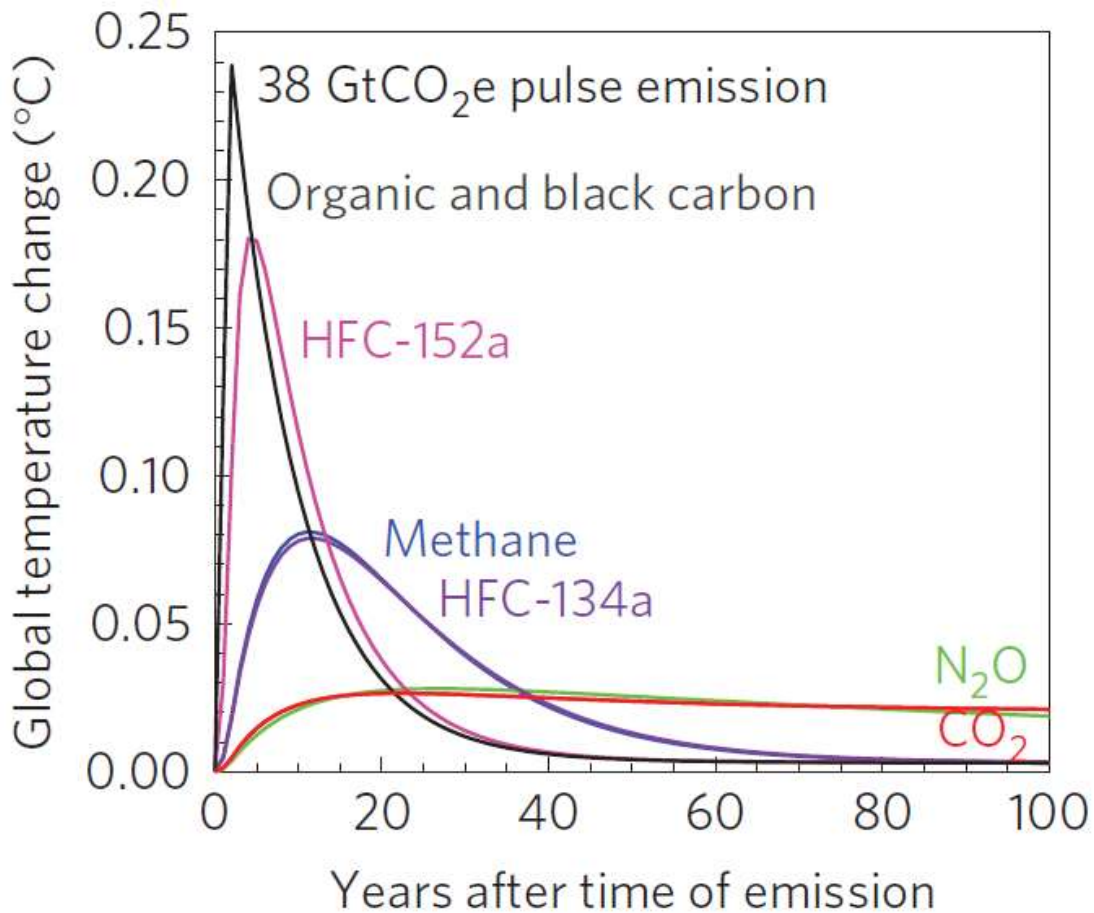
Figure 6 Global temperature change through time due to an equivalent pulse of emissions of different climate forcers when weighted by GWP100. The greater short-term warming caused by methane (blue line) versus longer term warming due to CO_2 (red line) is apparent. NB: Reproduced from Allen et al (2016, Fig 2a) for illustration.

This report considers the relationship between the use of natural gas and the EU's commitments to avoiding dangerous climate change. As such, the total impact of releases of carbon dioxide and methane, the major contributing agents, from the full supply chain from production to end use combustion, must be accounted for. Various metrics are available that allow the different warming effects of agents to be compared, one to another, or combined in assessments of the climate impact of countries, technologies, supply chains or socio-technical pathways of development. This section outlines the primary metrics that are used in climate and energy policy, and as Tanaka et al (2013) summarise, i) their scientific underpinnings, ii) relevant policy considerations, and iii) the inherent value judgements made in selecting one over another. The section concludes by discussing the most appropriate choice for this particular policy issue.

4.1.1 Emissions metrics

Global Warming Potential (GWP) is the most widely used metric for comparing the climate change impact of different WMGHGs in national and international climate policy and in "carbon footprint" studies that assess the lifecycle impacts of goods or services. Without GWP and similar metrics, multiple gas inventories would have to be reported and interpreted by data users for each impact assessment. The unit "tonnes of CO_2 equivalent", tCO_2e, calculated using an emissions metric is a straightforward means of accounting for climate impacts where multiple sources of GHGs are involved. GWP was introduced by the IPCC through its First Assessment Report (FAR, 1990) and subsequently adopted by the UNFCCC Kyoto Protocol. GWP is calculated by integrating, i.e. summing, the radiative forcing, i.e. the additional energy added to the atmosphere, of a pulse emission of a gas through a specified time horizon. Relative GWPs, for non-CO_2 GHGs, divide the

absolute value of heat trapping effect by the equivalent for CO_2 over the same period to give a comparative measure. This approach is therefore consistent with Life Cycle Assessment (LCA) practices, which favour comprehensive measures summed through time and across space (Cherubini et al, 2016), to facilitate comparison between technologies or supply chains.

The integration period for GWP is typically chosen as 100 years, however, it is often also calculated for 20 year and 500 year horizons. There is no "correct" horizon from a physical science perspective, rather it is a matter for those using the metric to consider their purpose. 100 years appears to have been adopted through a process of "inadvertent consensus" (Shine, 2009) and then integrated into international policy and carbon trading legislation. However, 100 years is a very short horizon in comparison to geological and ecological timescales, but rather longer than the atmospheric lifetimes of many SLCPs.

The choice of time horizon can make a substantial difference to the value of a metric. If a gas has a very long atmospheric lifetime then its GWP tends to increase with the time horizon. Conversely, short-lived gases, even those with very powerful heat trapping effects, tend towards low GWP values when considered over a long time horizon as their initial impact is averaged over the period. When a horizon is chosen for an impact assessment, it explicitly demarks the limit of consideration of the effect of the emission. GWP_{100} for instance ignores the effect of some gases many years into the future, when a large fraction may still be left in the atmosphere. CO_2 for instance has an atmospheric lifetime of centuries and CF4 persists for millennia. Conversely, GWP100 undervalues the instantaneous radiative forcing effect of methane leakages in the short term, however, in neither case does GWP illustrate the contribution to temperature change.

One of the strengths of GWP's basic formulation is that calculated values are not climate model dependent,[17] although consequently it does not relate gas emissions to the climate's behaviour. GWP is therefore criticised as being inappropriate for policies aligned to temperature based targets.[18] An alternative metric, Global Temperature Potential (GTP) does, however, make this connection. It identifies the temperature increase due to a pulse of emissions at a specified later point in time. For instance, the GTP_{20} for a tonne of methane released in 2017 indicates the resulting temperature rise in 2037, relative to the release of a tonne of carbon dioxide. It does not relate to the impact up to that point in time, or beyond it.

Considering the objectives of this report, life cycle assessments, emissions inventories and studies examining the climate impact of energy technologies or energy systems predominantly use GWP as the metric to relate methane to CO_2. Whilst GTP is a preferable metric for relating emissions to climate policy objectives expressed as temperatures, such as the Paris Agreement, the results of LCAs and other assessments are rarely calculated and reported in this way. Therefore, the limitations and implications of using these GWP values must be borne in mind.

There are two further issues of consistency that must also be considered i) the numerical value of the metric (quantitative consistency between studies) and ii) the choice of metric in relation to the use of the data (qualitative consistency with policy objectives).

4.1.1.1 *Quantitative consistency between studies*
As noted previously, the numerical value of a direct impact GWP factor is not determined by a time evolving climate model; it is calculated from the underlying physical characteristics of the atmosphere and the radiative forcing due to a small addition of a particular agent. However, successive studies have refined the

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[17] GWPs are typically calculated including indirect radiative forcing effects, due to *inter alia* changes in stratospheric water vapour, tropospheric ozone and cloud formation, but not always carbon-cycle feedbacks that require an explicit climate model of this effect.

[18] As IPCC AR5 highlights, the acronym is somewhat misleading and "relative cumulative forcing index" would be a better descriptor (IPCC WG1 (2013), p711).

understanding and representation of these characteristics and update the GWP metric values. Table 5 details the GWP values recorded for methane in successive IPCC assessment reports. Most recently, AR5 provided estimates of GWP and GTP including carbon cycle feedbacks[19] (e.g. reductions in oceanic and terrestrial biospheric uptake of CO_2 as a consequence of warming), which tend to increase the value of longer-lived GHGs more than SLCPs. The figures for GWP and GTP including carbon cycle feedbacks in AR5 were based on a single study (Collins et al 2013) whose primary objective was to investigate metrics for regional warming. The IPCC's judgement was that these values were more likely to better represent a metric than the non-feedback values, despite additional uncertainties, but further research was requested. Recently, Etminan et al (2016) have reported that methane's direct GWP_{100} should be increased by ~14% to offer a better representation of its radiative transfer effects in shortwave infrared wavelengths. Gasser et al (2017) have built on this body of work and recalculate GTPs and GWPs in addition to accounting for carbon cycle feedbacks for all gases and metrics. This has resulted in some limited increase in GWP values, relative to those cited in IPCC AR5, but reductions in GTPs. The radiative efficiency update has the greatest impact in this regard as the revised carbon cycle feedback time profile peaks between 30 and 40 years after emissions then falls away in comparison to the Collins' feedback function which rises in a similar time frame but remains high indefinitely.

Table 5 Values given for GWP and GTP metrics in IPCC reports with latest updates on radiative efficiency and carbon cycle feedbacks.

Source	GWP		GTP	
	Cumulative forcing over 20 years	Cumulative forcing over 100 years	Temperature change after 20 years	Temperature change after 100 years
IPCC FAR (1990)	63	21	-	-
IPCC SAR (1995) and Kyoto Protocol (1997)		21		
IPCC AR4 (2007)	72	25		
IPCC AR5 (2014)	84	28	67	4
IPCC AR5 (2014) with carbon cycle feedback (Collins et al 2013)	86	34	70	11
Gasser et al (2017) AR5 updated RE, no cc feedback	96	34	65	8
Gasser et al (2017) AR5 updated RE, +cc feedback	96	34	66	9

It should also be noted that the uncertainties in the calculation of GWP values, predominantly due to uncertainties in the underlying forcing due to CO_2 as the reference gas,[20] are presently considered to be ±30% and ±40% for 20- and 100-year time horizons respectively (IPCC WG1, 2013). Uncertainties in GTPs are

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[19] The carbon cycle feedback has previously been included in the calculation of absolute GWP and GTP for CO2 but not for the other gases so this corrects the inconsistency in the relative measures.

[20] The lifetime of CO2 is a special case for WMGHGs; its loss from the atmosphere is determined by multiple non-linear processes, with internal feedbacks, rather than an exponential decay due to chemical reactions or physical deposition.

higher due to additional dependencies on climate sensitivity and therefore proposed as ±75% for methane's GTP_{100}.[21]

4.1.1.2 Qualitative consistency with policy objectives

Reports of methane emissions' impacts are often conveyed with both 100 year and 20 year GWPs. The shorter horizon is variously justified in reference to "tipping points", thresholds in the climate system, or the proximity of present temperatures and trends to 1.5°C/2°C policy objectives (e.g. Shindell et al 2012, Howarth et al 2012, Howarth 2015, IASS 2016). It is important to understand the implications of this combination of metric and time horizon to represent the impacts of SLCPs.

First, GWP does not represent temperature change or the human or ecological impacts of climate change, although this is often how it is presented. If one is interested in the increase in temperature that may lead to impacts on ecological or human systems, then GTP is a superior metric. As described earlier, GWP represents a physical effect of the gas, not the climate response that would be relevant to biophysical thresholds, or biological or human systems that would be sensitive to the rate of change in an element of the climate e.g. sea level rise, maximum seasonal temperature. Second, the relevance of a 20 year time horizon, is itself questionable. Given the inertia in societies and infrastructure, not to mention the climate system or the lengthy duration over which CO_2 emissions exert a warming effect, it is highly unlikely that global temperature rise will peak before 2040. A 20 year horizon provides an indication of relative contributions of a pulse of emissions during that 20 years (or at that 20 years hence for GTP), but not the contribution to the extent of warming at the time of long-term temperature stabilisation or the rate of warming. Basing policy decisions on either the energy trapped (GWP) or temperature rise (GTP) due to a particular technology choice after this period is therefore questionable.

Non-linearities in climatic response and the potential for abrupt changes have been cited as a justification for selecting a near term horizons. The potential for large, irreversible changes in elements of the climate system arising from small changes near a threshold has been suggested for areas of Amazon rainforest transitioning to grassland, releases of methane from thawing sub-arctic permafrost or clathrates, the collapse of the West Antarctic ice sheet, or the shutdown of the Atlantic Meridional Overturning Circulation (AMOC) (Lenton et al 2011). Such changes may also cause feedbacks in the climate system or may be limited to isolated changes in that element e.g. ecosystem change from coral dominated reefs to algae dominated reefs. The risk of tipping points being activated is expected to increase with temperature rise, with Arctic and coral reef ecosystems identified as at medium risk before 1.5°C, or 2040, although confidence in these findings varies between elements (IPCC 2014 SR Table 2.3; IPCC 2013, WG1 Section 12.5.5). Furthermore, in some cases physical or ecological state shifts are related both to the extent of temperature rise and the time period for which the rise persists (e.g. collapse of the Greenland ice sheet). Whilst such mechanisms are substantive reasons to mitigate climate change, the possibilities they present do not provide a compelling justification to use a 20 year time horizon in contemporary policy making. Rather, they suggest that a lower stabilisation temperature objective would be appropriate.

In comparison to SLCPs, a pulse release of CO_2 creates a permanent rather than a temporary warming effect. Delays in action on CO_2 lead to greater temperatures in the long-term, which is not the case for methane and other SLCPs. Quantities of emissions with equivalent weighted values can therefore result in different climatic consequences due to the interplay of the strength of forcing with the lifetime of the GHG concerned. Figure 6 above illustrates the temperature change at different points in time for emissions with equivalent tCO_2e values, highlighting the strong, short term effect of methane relative to CO_2.

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[21] Although subject to substantial uncertainty itself, the inclusion of carbon-cycle feedbacks does not substantially increase the uncertainty in GTP values as it is a relatively small part of the overall effect (Gasser et al 2017).

For this and other reasons, some argue for multiple parallel accounting approaches where gases with similar lifetimes are grouped rather than relating all to a common (CO_2) denominator (Pierrehumbert et al 2015). By way of resolution of these ambiguities in climate outcomes, Allen et al (2016) propose to relate one off pulses of long lived GHGs to sustained reductions in annual emissions of SLCPs. This approach more closely relates the climatic effects of the two groups of forcing agents, as SLCP emissions rates need to be stabilised at a reduced level, determined by the stabilisation temperature target, whilst emissions of cumulative pollutants such as CO_2, always need to be taken to zero at some future point in time. However, such an approach is quite different to current fixed quantity accounting used in policy, such as the UNFCCC or EU, and analysis, life cycle assessment and carbon accounting.

Figure 7 below, depicts the different temperature effects of sustaining emissions at 2011 levels for the next century. Cumulative GHGs, CO_2 (red) and N_2O (green), continue to cause rising temperatures, however, sustained emissions of SLCPs, methane (blue) and black carbon (black) tend to a static temperature change. For methane, this can be understood as a "continuous wave" of peaks of short term impact (see Figure 6) moving through time, as the gas leaves through sinks but is replenished by emissions. In effect methane reaches a constant atmospheric stock maintaining the temperature change but not contributing to increasing temperature. In contrast, for longer lived gases such as CO_2 the red line illustrates accumulation of the gas in the atmosphere and the ongoing increasing temperature change it causes.
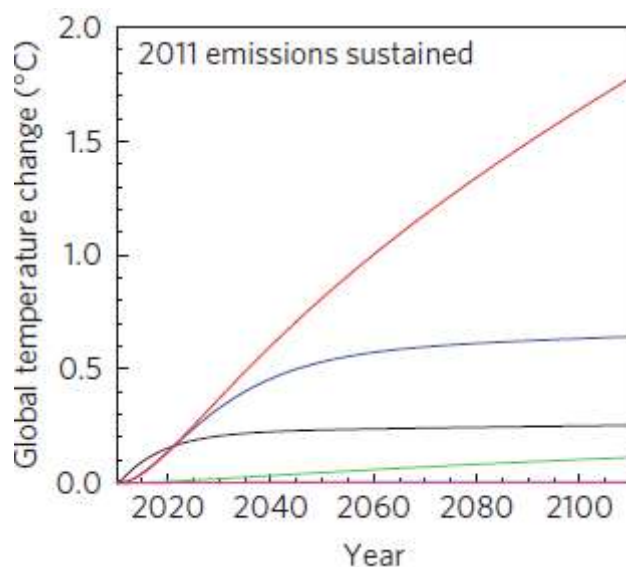
Figure 7 The consequences of failing to mitigate GHGs from present levels for CO_2 (red), methane (blue) black carbon (black and N2O (green). NB: Reproduced from Allen et al (2016, Fig 2e) for illustration.

It is clear that emissions reduction needs to proceed on all major forcing agents simultaneously, short lived and long lived, to achieve the Paris Agreement objectives. As Allen et al (2016) clearly state, CO_2 mitigation "…remains the *sine qua non* of climate stabilization". Without compelling evidence for near term stabilisation of warming, we conclude that the 20 year time horizon, for either GWP or GTP, is not useful to current energy system policy making. A 100 year time horizon for GTP tends to understate the relevant warming effects of SLCPs if stabilisation is necessary before 100 years. Conversely, GWP100 overstates SLCPs contribution to peak temperature change unless the peak is within the atmospheric lifetime of the SLCP.

4.1.2 Implications for supply chain life cycle assessments

Metrics are often used in "carbon footprint" and inventory reports without consideration of their relevance to the issue at hand. The focus of this report is to understand the climate change impact of natural gas supply chains within the framework of the Paris Agreement. This requires the metrics used to be aligned

with temperature objectives of the Agreement, which the most commonly reported metric of GWP is not intended for. The numerical value of the GWP100 metric for methane is comparable to its GTP for a 40 year time horizon; they are both calculated as approximately 30. Fortuitously, the 40 year horizon is approximately the timescale relevant for stabilisation of climate change "well below 2°C" (Allen et al 2016). Therefore, the numerical values of climate change impacts, calculated with reference to GWP100 in much of the literature related to natural gas systems, weight CO_2 and methane appropriately for mitigation according to the Paris Agreement's objectives.

Recent refinements to the calculation of GWP and GTP metrics have suggested ~20% increase in the GWP 100 value cited in AR5 to 34 (Gasser et al 2017). Considering the large uncertainty in estimating both emissions and climate response there is little to be gained, in gross impact assessment terms, by re-basing all studies to a common value.[22] Findings from emissions quantification studies that use a multiplier of ~30 for relating methane and CO_2 emissions are therefore applicable to this policy problem and are used as the basis of the remainder of Section 4. This approach is subject to the caveat that if future mitigation does not proceed to the necessary extent, and peak warming occurs at a higher temperature later in the 21st century, this approach will have over-emphasised the importance of near term methane in mitigation up to that point.

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[22] It should be noted that this is 50% greater than the IPCC SAR (1995) value, 21, used by the Kyoto Protocol and subsidiary mechanisms.

4.2   Boundaries and scope

A key issue in quantifying the contribution of any technology, supply chain or region is clarifying the boundaries of assessment. These vary from study to study according to purpose, preference and data availability. Where emissions are reported in this section we will endeavour to make this on a comparable basis or include caveats and clarifications. First and foremost is to note that whilst methane emissions are the focus of this report, there are additional carbon dioxide emissions from the production of natural gas, for instance in providing energy to transport the gas. Studies discussed below and presented in Appendix B are therefore indicated where they provide a combined estimate of non-combustion greenhouse gases and where they are for methane emissions only. Before considering the data, it is worth also noting a number of other issues.

4.2.1   Supply chain stages

Emissions of greenhouse gases vary substantially across the full supply chain from exploration to end use consumption. Whilst we will not provide an exhaustive breakdown and comparison, it is worthwhile introducing the major steps and sources of emissions for consideration. It should also be noted that not all stages are included in all supply chains.

Any given estimate of emissions will refer to one or more of the below stages, either for specific sites, sampled sites to provide data to model emissions from a larger population of sites, or a defined geographic area capturing the emissions from a number of stages.

Stages may be located entirely within a geographic entity or distributed through space. For instance, for fossil fuel producing nations, national emissions inventories may be dominated by the production and early transport stages. Conversely, importing nations may report emissions solely from some elements of transport, distribution and consumption. Such geographic issues matter for policy and reporting purposes, but not in climatic terms as the dominant warming effect of methane occurs globally. Section 4.3.2 discusses this particular issue.

Life Cycle Stage	Activity	Emissions Sources
Production	Exploration	Site surveying
		Test drilling
	Extraction	Well construction
		Drilling
		Well completion
		Flaring (incomplete combustion)
		Workovers (including liquids unloading)
		Gathering facilities
		Pneumatic Controller (PC) / valve fugitive and vented emissions
		Condensate tank vents
		Site remediation
	Processing	Compression
		Dehydration
		Acid gas removal
		Gas liquids removal
		PC/valve fugitive emissions
Transport	Transmission Pipeline	PC/valve fugitive emissions
		Compression
		Pipeline leakages
		Pipeline construction
	LNG	Liquefaction
		Boil off leakages
		Transport fuel
		Regasification
	Storage	Compression
		PC/valve fugitive emissions
	Distribution Network	Pipeline leakages
End Use	Consumption	Incomplete combustion
		PC/valve fugitive emissions

The LCA approach is to present the impact of a complete supply chain, from exploration to consumption, typically by summing secondary sources or making assumptions guided by expert knowledge. Whilst comprehensive, these studies often rely on opaque data sources, assumptions and inconsistent boundaries. Individual figures should therefore not be taken, *prima facie,* as comparable. Meta-analysis of LCA outputs and composites of empirical studies are valuable in such cases and Balcombe et al (2016) present the most up to date assessment of the full natural gas supply chain.[23] This paper is a comprehensive meta-analysis of 250 prior studies, both primary measurements and secondary sources. In our view, this represents the most

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[23] The study conducted a thorough review of existing research including all supply chain routes for which studies had been conducted, for both conventional and unconventional, onshore and offshore production, pipeline and LNG transport. It made no geographic or industrial exclusions, data sources were only discounted on the basis of robustness.

useful resource available for a synoptic view of methane emissions from the natural gas supply chain. The paper reports that there is a wide range of estimates in the literature, some of which come from studies with inconsistent assumptions or rely on historic secondary data that may not be currently representative. To improve the reliability and applicability of their findings they present a second "constrained" data set, selecting the most recent and robust studies for each stage of the supply chain using primary data where possible. They also note a highly skewed distribution at the upper end of their analysis, in some cases two orders of magnitude greater than the median, and therefore report the 95th percentile as the limit of a likely upper bound. This approach recognises that it is unlikely that maximum values would ever coincide along a single supply chain.

In addition to these summary findings, the tables in Appendix B present a number of other LCA and primary measurement studies that provide indicative values for specific supply chains. It should be noted that the some of the underlying data is also reported as part of Balcombe et al (2016).

4.2.2 Supply chains of particular relevance to European energy policy

The largest producers of gas in the EU28 are the UK and the Netherlands, together representing approximately 70% of production. Most gas consumed in the EU28 is imported, with an energy dependency ratio, net imports per unit of gross inland consumption, of approximately 70% (Eurostat source data: nrg_103m, nrg_124m, nrg_134m). Imports are currently dominated by four sources: pipeline gas from Russia (42% of imports to the EU for 2016), Norway (34%), and Algeria (11%) and LNG (13%) from diverse sources, largely Qatar, Algeria and Nigeria (DG Energy, 2016). With this in mind, example data from LCAs specific to these sources are included; Stamford and Azapagic (2012), MacKay and Stone (2013), Exergia (2015), Tagliaferri et al (2017), and Safei et al (2015).

FIGURE 8 – EU IMPORTS OF NATURAL GAS BY SOURCE, 2014-2016
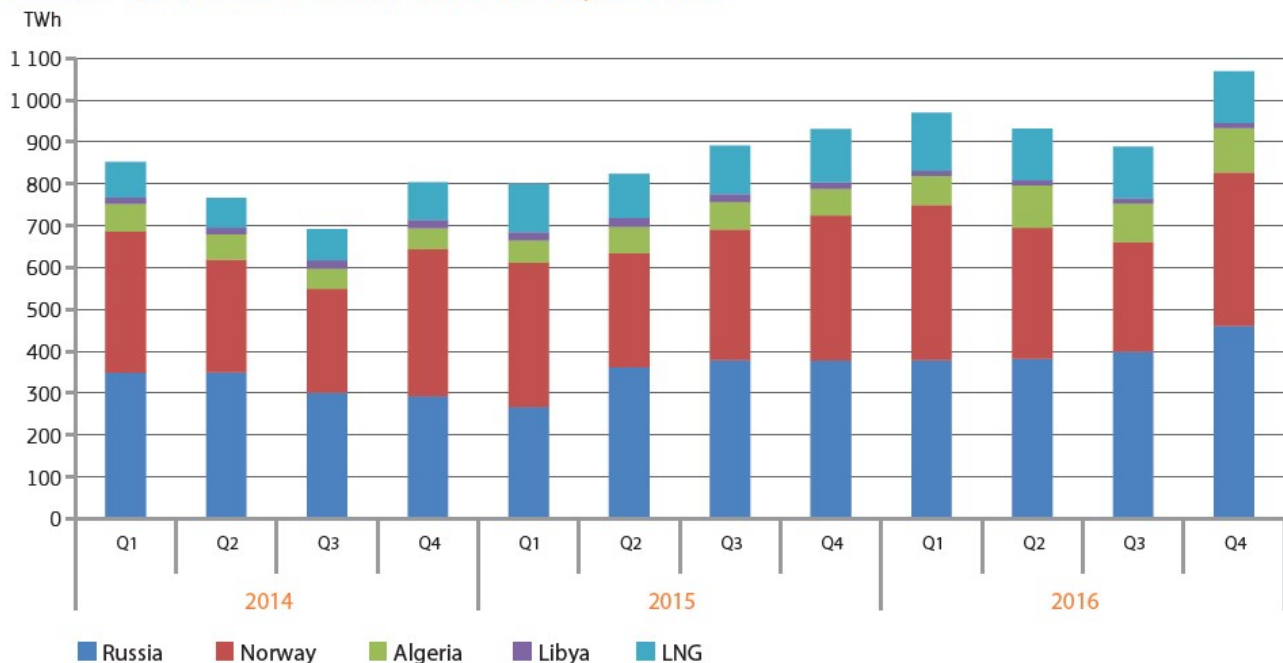
Source: Based on data from the ENTSO-G Transparency Platform
Russian deliveries to Finland are reported from 1 June 2014; deliveries to Estonia and Latvia are reported for a limited period (Narva from 15 June 2015 to 10 December 2015, Varska and Misso Izborsk from 26 May 2015)
Norway to UK flows reported by ENTSO-G include some gas from UK offshore fields, resulting in an overestimation of Norwegian imports.

Figure 8 EU Imports of Natural Gas, source DG Energy (2016).

In future, LNG exports from the USA and Australia are expected to increase substantially, as new liquefaction facilities come on line and shale gas and coal seam gas production continue to grow (IEA, 2017). Whilst this will contribute to global supply, economic and contractual considerations will determine how much is consumed in Europe. US shale gas LCA estimates, including high profile studies such as Howarth et al (2011) and Skone et al (2014), are harmonized and summarised by Heath et al (2014), and are therefore also included for comparison. Prospective LCAs for shale gas production in the UK from MacKay and Stone (2013) and Stamford and Azapagic (2014) are reported in Table 8, however, they are not calculated from direct measurements of UK production as that is yet to commence.

4.2.3   Primary data from USA

There is limited up to date academic literature documenting measurement campaigns focussed on European gas infrastructure and supply chains. However, a number of systematic US measurement campaigns, delivered by a range of academic and commercial institutions and in large part supported by the NGO the Environmental Defence Fund, have published detailed results in recent years. Some of these site-specific studies were dependent on the cooperation of natural gas production companies, private and civic infrastructure operators, larger scale atmospheric sampling studies were independent of such access arrangements.

Although not of direct relevance to EU supply chains, these data are among the most thorough and well described in the literature to date, illustrating key sectoral and measurement issues that are most likely applicable to other geographies (see Section 4.4 for discussion). Data from both top down and bottom up studies, are presented in Appendix B with the relevant scope identified. These studies also inform our perspective on other measurements and assessments that are directly relevant to EU supply chains. The repeated findings of i) skewed distributions of volume of emissions amongst assets and events, and ii) underestimates of existing inventories suggest that these features are likely to be encountered in other gas production and distribution systems.

4.2.4   Distinguishing emissions from natural gas supply vis-à-vis other fossil fuels

Methane emissions arise from all fossil fuel supply chains, and may be regarded as either a hazard or an additional revenue stream. Deliberate production of natural gas from coal measures, variously known as coal bed methane (CBM) or coal seam gas (CSG), is profitable in some locations. Likewise, natural gas production can be supported by the sale of higher value oil and intermediate fractions known as natural gas liquids. Each of these industries is therefore a potential source of natural gas for sale, and also substantial methane emissions if it is not managed effectively. Disentangling the effects of these sources from that of "the natural gas industry" proper is challenging and in some cases requires arbitrary boundaries. In the course of this review we have tried to be explicit as to where estimates relate to co-production systems e.g. oil associated gas or vice versa, however these distinctions are not always consistent between sources. Large scale e.g. satellite studies, using on top down methodologies face particular difficulties in this regard.

4.2.5   Normalisation of data to common units

In presenting the data in this review, individual results have been normalised to additional methane emissions, as CO_2eq (GWP100), relative to CO_2 from the combustion of delivered methane. As detailed above, these units allow comparison between supply chains, and are not subject to further assumptions about end use technology performance (e.g. vehicle, boiler or power plant efficiency). This normalisation is possible as methane emissions are often given as a percentage of throughput, following assumptions about the methane content of natural gas. For comparability, the constants used by Balcombe et al (2016) have been taken throughout, namely GWP100 for methane: 34 $kgCO_2$e/$kgCH_4$, methane fraction of natural gas

(vol/vol): 80%, energy content of natural gas (HHV) MJ/m^3: 38.1, methane density at 20°C and 1 atmosphere: 0.67 kg/m^3. Methane fraction is not constant throughout the supply chain (processing intentionally raises this), which may introduce an underestimate of approximately 10% in some cases. Nevertheless, given the broad ranges and other sources of potential uncertainty this is not considered problematic. These constants imply combustion emissions of 2.05 MtCO$_2$ per bcm natural gas.

4.3   Emissions from major EU supply chains

The data presented in Figure 9 and Appendix B suggest that the rank order of additional (non-combustion) supply chain GHG emissions, from lowest to highest, is 1) conventional North Sea production, 2) unconventional resource, short distance pipeline, 3) LNG, 4) long distance (Russia) pipeline. The additional emissions of LNG and long-distance pipeline are approximately double those of short distance conventional production. Abrahams et al (2015) assume that upstream emissions from Russian production and transmission have an additional 3% methane leakage over average US gas, and conclude from this that LNG exports from the USA to Europe are more favourable than long distance pipelines, however, they do not provide a source for this additional leakage estimate. Without specific reference to Russian supplies, the sensitivity analysis presented in Heath et al (2014) identified pipeline distance and pipeline leakage rate as the dominant variables, whereby a doubling of distance would lead to a 30% to 35% increase in non-combustion GHG emissions.

Significantly, it should be noted that the data from the examples in Table 8 do not derive from intensive measurement campaigns as per the US studies discussed above so confidence in the precise values, or indeed how generally representative these rankings are, is low. The larger sample size of Balcombe et al (2016) would suggest greater confidence in the conclusion that the additional energy required for LNG transportation (for liquefaction, shipping and regasification) adds a burden for LNG of approximately an additional 20% over the total emissions from combustion and short-distance pipeline transport. Data from these meta-analyses and examples of supply chains are presented graphically in Figure 9 below.
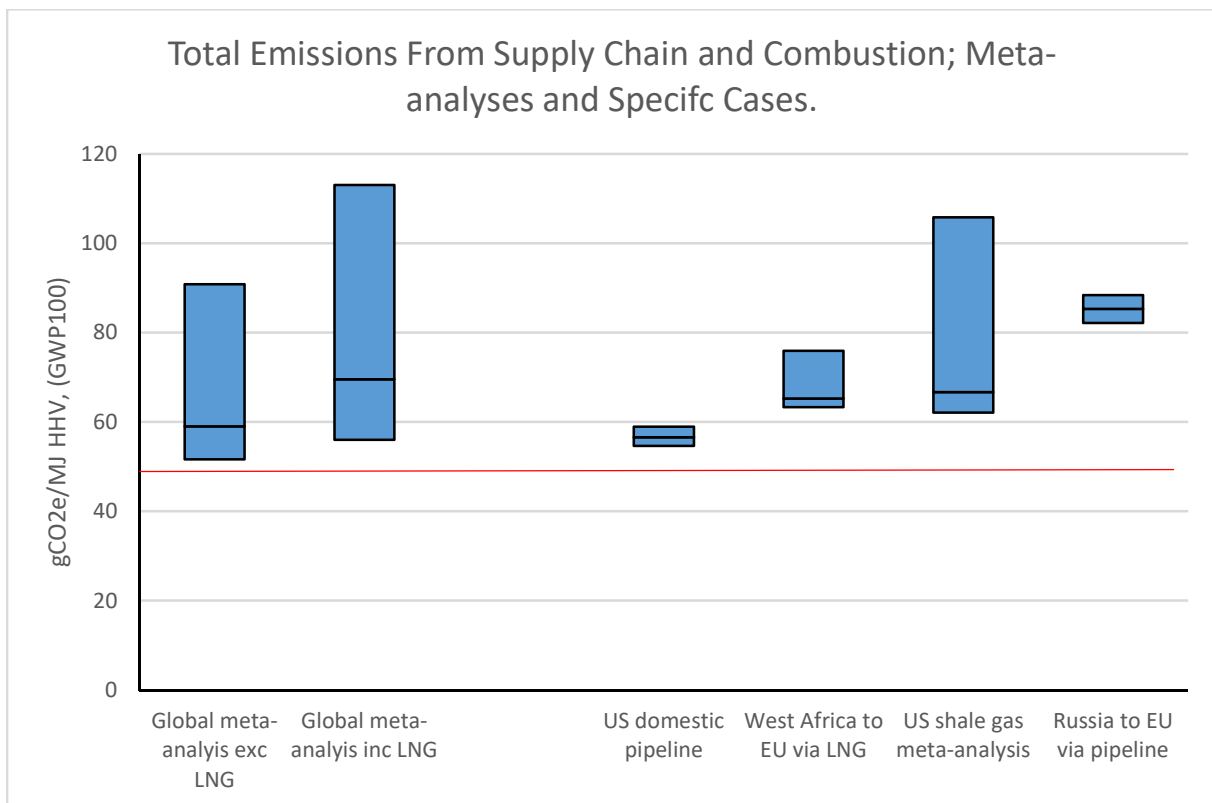
Figure 9 Estimates of total emissions from supply chain and end use combustion of gas from different sources. Data are from, in order left to right, Balcombe et al (2016), Balcombe et al (2016), Littlefield et al (2017), Safei et al (2015), Heath et al (2014), Exergia (2015). Definitions of ranges and central estimates are not consistent, see Appendix B for further details. The red line indicates CO₂ emissions from end use combustion taken as 48.4 gCO2/MJ HHV.

4.3.1 Relative proportions of methane and carbon dioxide emissions in the supply chain

The relative balance of climate impact between methane and CO_2 is largely dependent upon the rate of emissions of methane. Drawing on the data presented in Balcombe et al (2016), Table 6 presents this breakdown in the context of total emissions including end use combustion. For median values CO_2 dominates but this reduces towards the highest estimates observed. For non-LNG supply chains, just over half of supply chain climate impact is due to methane leakages for the median of their constrained estimate, whilst at the 95th percentile this rises to approximately two thirds. The proportions are similar for LNG supply chain estimates although the absolute quantities are greater for all but end use combustion.

Table 6 Proportion of methane and CO2 emissions from combined natural gas production and consumption, derived from Balcombe et al (2016)

| | Supply chain | | End use combustion |
	Methane	*CO₂*	*CO₂*
Supply chains exc LNG			
Minimum	6%		94%
Median	10%	8%	82%
95th Percentile	32%	14%	53%
Supply chains inc LNG			
Minimum	14%		86%
Median	13%	17%	70%
95th Percentile	35%	23%	43%

Because of the mixture of greenhouse gases, the relationship to the carbon budgeting framework is not straightforward. When considering the supply chain emissions in relation to climate policy, it should be noted that the carbon budgets presented in Section 2.1 have an allowance for short term warming due to methane emissions included as an overhead. Whilst the relative differences in short term warming due to methane are not directly transferrable to the carbon budget framework, the carbon dioxide from combustion in the supply chain is. In absolute terms (as per Figure 9), LNG supply chains were found to have approximately 50% greater CO_2 per unit of consumed gas at the 95th percentile of the constrained estimate than pipeline sources. This implies that in comparison to pipeline gas, LNG consumption will have a greater impact on carbon budgets than would be expected from simply looking at total supply chain emissions estimates.

It should also be noted that the estimates presented in Table 10 and Table 11 are for methane emissions only and do not include the CO_2 emissions from the energy required at each stage, nor from end use combustion.

4.3.2 Supply chain stages included within European climate change commitments.

As outlined in Section 4.2.1, production, transmission and distribution of natural gas consists of many stages that may be widely geographically dispersed. One consequence of this is that the emissions arising from these activities are attributed to different countries. The IPCC guidelines used by the UNFCCC international climate policy framework specify that only emissions arising within the geographic boundaries of a nation are assigned to that nation. Taking LNG produced in Qatar and shipped to the UK as an example, the methane emissions from the well site production and processing, and CO_2 emitted to produce the energy required for liquefaction are assigned to Qatar. Any LNG leakages during shipping, so called "methane slip", are allocated to international shipping under the IMO's jurisdiction with the CO_2 from fuel combusted in transit. Upon arrival in the UK, greenhouse gas emissions from handling, regasification, transmission, distribution and end use combustion are captured in the UK, and currently EU, emissions inventories.

Balcombe et al (2016) capture the range of emissions reported for different elements of the natural gas supply chain. End use combustion is the largest share of the climate change impact for all but the very highest end of the LNG range, ranging from 94% (lowest absolute emissions) to 53% (highest absolute emissions) for pipeline transmission versus 86% to 43%, respectively, for LNG (see Table 6 above). These combustion emissions will always be captured within EU climate change commitments. Transmission, distribution and storage are the next highest values, totalling 8% for the median estimate, followed by processing at 7%. Depending on the supply chain the former stages will largely be captured within the EU, the latter only for production based within the EU e.g. North Sea Continental Shelf. For LNG, the most intensive emissions step is liquefaction of processed gas, accounting for 9% of the median total and occurring outside of EU reporting and control.

All other stages are less than 1% of total for the median estimate, however, supply chains with poorly regulated and enforced production environments may be expected to have greater leakage rates and this would tend to increase both absolute amount and proportion attributed to production. A recent review found inconsistencies in reporting within the EU and in its Russian and US supply chains. Although inventories were compliant with UNFCCC reporting requirements the study found limited empirical validation of the emissions factors used to report inventories (IASS 2016). In light of this, and the broad variability and lack of accordance with official bottom up estimates in many field studies of US production environments, it is premature to draw precise numerical conclusions. Detailed atmospheric research to support inventory production, such as the pan-European Integrated Carbon Observation System (ICOS), may go some way to resolving these matters with EU boundaries but there is a long way to go in implementation and enforcement elsewhere.

It should also be noted that were carbon capture and storage to be pursued within the EU, associated with gas fired power plant and industrial facilities, then supply chain sources of emissions would represent a much larger proportion of the total quantity of emissions reaching the atmosphere. This use case therefore presents a substantial risk of "carbon leakage" with emissions increases associated with EU consumption occurring outside of EU regulatory control.

4.4   Discussion of data sources

There is a large spread of potential values for non-combustion emissions in the natural gas supply chain, from an additional 2% to more than 200%. The primary measurement data give some indication of why this may be but it is unavoidable that currently there are large uncertainties in the emissions associated with the natural gas supply chain.

4.4.1   Primary data, top-down vs bottom-up estimates

Top-down estimates (Table 10), where atmospheric measurements from aircraft or ground based stations are related back to industrial sources through transport models, are often greater than bottom-up estimates for a comparable geographic area or supply chain stage (Table 11). Although top-down methods capture a complete atmospheric sample they have large numerical uncertainty ranges because of the nature of the process of allocating back to sometimes diverse sources in addition to fossil fuel industries (livestock, geological seepage, landfill sites). Inventories, such as those developed by the EPA, EDGAR, and GHGRP, typically under-estimate methane emissions in comparison to top-down measurements. For instance, use a national dataset of atmospheric monitoring Miller et al (2013) find EDGAR v4.2 (2008) may underestimate fossil fuel emissions by a factor of 4.9 ± 2.6 times. This is also the case where site specific measurement programmes find leakage at the relatively low end, for instance, Karion et al (2015) suggest that the EDGAR inventory underestimates the Barnett Shale oil and gas sector emissions by a factor of almost 5. Satellite studies of US emissions of methane from all sources, find greater accordance with the EPA inventory (2014) in 2004 (Wecht et al 2014) than in 2012 (Turner et al 2015). Wecht et al (2014) noted that in 2004 the EPA inventory showed no discrepancy with their estimate of oil and gas production sources of methane, but a 40% underestimate of livestock emissions. A later review of multiple top-down sources concluded that there has been an increase in anthropogenic emissions of over 30% in the decade from 2004, which is not captured in bottom up inventories (Turner et al 2016). However, Turner et al (2015) note that although the total underestimate in the EPA inventory is well evidenced, attribution to fossil fuels and livestock is ambiguous and the rise observed in satellite data was not spatially coincident with regions showing strongest growth in oil and gas production (Turner et al 2016).

Peischl et al (2015) use airborne sampling to report emissions from three regions that account for 20% of national natural gas production, but over half of US shale gas production, so may be more representative of this gas source. They find that supply chain emissions add between 2 and 28% to the climate change impact of burning the produced gas. Kort et al (2014) show a persistent, constant elevation of methane levels in the Four Corners region of the US (the junction of Arizona, Colorado, New Mexico and Utah) across the period 2003-2009. This is 3.5 ± 0.5 (2σ) times greater than the EDGAR v4.2 emissions inventory for the fossil fuel industry (coal, oil and natural gas) but is not allocated to gas production for comparison in Table 7. Airborne surveys of the same area in 2015 (Smith et al 2017) find similar levels of methane emissions despite a 34% decrease in gas production since the prior study. However, there has been a 260% growth in oil production in the same time and the authors note that other more specific aerial surveys have identify higher prevalence of highly emitting infrastructure (e.g. storage tanks) in mixed and oil dominated basins, such as Bakken, than gas dominated region (Lyon et al 2016). In cases where gas is associated with higher value liquids or oil, there may be limited economic incentive to reduce emissions and increase volumes of saleable gas. In such circumstances, regulation and enforcement, informed by empirical and statistical findings, are essential.

Schneising et al (2014) observe increases in atmospheric methane using satellite observations by comparing averages over the periods 2006-2008 and 2009-2011. When combined, the absolute increases of 990±650 ktCH$_4$/yr for Bakken and 530 ± 330 ktCH$_4$/yr for Eagle Ford, are equivalent to 24% of the reported 2011 US national methane emissions from natural gas systems (US EPA, 2011). However, the methodology used

makes is difficult to compare this study to others. Leakage rates are reported at 10% ± 7% methane produced as a proportion of the increase in energy production between the periods, which includes oil, the dominant output of these fields. As well as being problematic for comparison with other studies, Peischl et al (2016) note that this would translate to approx. 44% ± 32% by volume of gas produced, which is very much higher than the other measurements listed above and may not be an appropriate metric due to the nature of the fields. There is also a substantial discrepancy between these two studies in the methane content of natural gas used to calculate the percentage leakage; Peischl et al (2016) use a value of 47% ± 13% from a Department of Energy measurement campaign in the area, reflecting the larger proportion of longer chain hydrocarbons produced by these wells, whereas Schneising et al (2014) assume 93%, which although more typical of gas wells is not representative of this area. Kort et al (2014) did not identify methane enhancement of this scale in the Bakken region in data collected before 2009. Whilst the Energy Information Administration records meaningful production of oil in the Bakken region prior to 2009, substantial growth in gas production occurred afterwards (EIA 2013).

Top-down studies are less prone to missing emissions sources due to their sampling strategy not coinciding with emissions in time or location. For instance, Lavoie et al (2017) found that facility scale methane emissions from gas handling at power plants were substantially underestimated relative to inventories.

At the other end of the supply chain, there may be an additional contribution from abandoned oil and gas wells. A study of 19 wells in Pennsylvania found a highly skewed distribution of emissions with the mean detected emissions approximately three orders of magnitude greater than the median (Kang et al 2014). In this case, the small sample and wide uncertainty on the measurements themselves limits the broader applicability. A larger study of 138 wells (Townsend-Small et al, 2016) found that most abandoned wells don't continue to emit methane, but 6.5% do. The largest contributors were the small proportion of unplugged wells. Taking these into account the study estimates abandoned wells contribute <1% to overall methane emissions in the study area (Wyoming, Ohio, Colorado, Utah). Although small, using these findings as an emissions factor suggests abandoned wells may contribute an additional quantity to oil and gas sector inventory in the range 1.9 to 4.3% of total methane emissions. In the only European study identified, Boothroyd et al (2016) reported that 30% of samples abandoned wells had elevated methane concentrations in soil gas, however the quantification of the flux shows low values with a very large uncertainty range (364 ± 677 kg CO_2eq/well/year) due to the relatively insensitive sampling equipment.

A much more significant phenomenon identified in the empirical research is highly skewed distributions of sources, sometimes termed "super-emitters". Bottom-up studies, which closely sample sites and scale up according to counts of similar machinery or processes, have repeatedly identified that a small proportion of equipment is responsible for a large proportion of emissions. From a meta-review of 18 US measurement studies, Brandt et al (2016) concluded that 50% of methane emissions typically arise from 5% of leaks. Their statistical analysis suggests that the uncertainty ranges given in these bottom-up studies are too narrow, the small number of leaks will be disproportionately under represented by fitting a parametric distribution, and that more facilities should be sampled in any given study to ensure that sufficient low frequency, high volume leaks are encountered and that sample data are representative of the population of leaks. Furthermore, the problem is not solved by aggregating samples across studies due to differences between the sampled populations, and the study recognises that the persistence of leaks and their distribution through time is not yet understood.

The distribution system, linking high volume transmission pipelines, to small scale consumers over urban networks are not well represented in the research literature. Jackson et al (2014) report the results of the 2011 Pipeline and Hazardous Materials Safety Administration (PHMSA) survey as a mean rate of "lost and unaccounted" (LAU) gas as 1.6% but with operators reporting in the range zero to 11%. The presence of cast iron mains piping is particularly associated with high leakage rates. This may be one part of the supply chain

where infrastructure improvements have reduced emissions through time, for instance in comparison to measurements taken in the 1990s that were used for 2011 EPA inventory (Lamb et al 2015). Once again there are discrepancies between top down and bottom up approaches, with McKain et al's (2015) top down research reporting emissions an order of magnitude higher.

In contrast to the above, Zavala-Araiza et al (2015) present coincident top-down and bottom up measurements for the Barnett Shale region. However, to do so, they employ i) intensive measurement campaigns that capture low frequency, high emissions sources, ii) statistical approaches that represent these, iii) accurate, up to date counts of facilities and their equipment types, and iii) measurements of a signature species to constrain fossil sources of methane in top down estimations. Their resulting estimate is at the low end of the studies reported above, with a central estimate of additional production emissions 15% of combustion. However, this is still 90% larger than the US EPA inventory (2014) and more than five times larger than the EDGAR v4.2 (2013) inventory for the same region.

Finally, it should be noted that allocating methane emissions between oil and gas production can be challenging where they are co-located. The measurements taken in the Four Corners region suggest that basin scale emissions do not always scale with gas and oil production (Kort et al 2014, Smith et al 2017). Rising oil production may lead to changing practices and greater methane emissions, but in light of Brandt et al (2016) and Lyon et al (2016), such findings suggest that at some scales emissions may be somewhat idiosyncratic and not correlate with production volumes. Likewise, it is also consistent with the notion that low productivity unconventional wells (low Estimated Ultimate Recovery, EUR) may have high proportional additional emissions due to the episodic nature of the emissions burden in this sector and that this has greatest influence at the upper bound of estimates (Balcombe et al 2016). Whilst the upper bounds of the range presented by Balcombe et al (2016) may not be representative of the sector as a whole it is reasonable to assume that they are representative of specific cases and that these are not negligible considering the discrepancy between top down measurements and bottom up inventories. It therefore appears to be premature to make precise statements of the emissions intensity for supply chains, located largely outside of the USA, that are as yet poorly sampled.

5   Conclusion

Climate change is being driven by the sustained output of anthropogenic greenhouse gases, with fossil fuel production, distribution and consumption the dominant contributors to these emissions. If we are to achieve the objectives of the Paris Agreement to hold *"…the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels"* it is imperative that energy systems globally are fully decarbonised within the coming three to four decades. For the EU, fossil fuels, including natural gas, can have no substantial role in an EU 2°C energy system beyond 2035.

With a rapid decline in deforestation and prompt reductions in process emissions from cement production, we have estimated the energy-only *global* carbon budget post-2017 necessary to deliver on the Paris temperature commitments ranges. At current rates of emissions from energy this relates to between 14 years, for an "unlikely" chance of 1.5°C, and 18 years, for a likely chance of 2°C.

Given the extent of existing greenhouse gas emitting infrastructure, it is highly unlikely that the Paris 1.5°C commitment is a viable mitigation objective. Only if "real" mitigation guided by the carbon budgets for a "likely" chance of 2°C are pursued and highly speculative Negative Emissions Technologies (NETs) prove to be successful at an early and unprecedented planetary scale, could 1.5°C be considered theoretically achievable.

The remaining emissions budget must be shared between nations and sectors. Assuming a peak in energy carbon emissions from the non-OECD region occurs between 2020 and 2025 (far earlier than anything countenanced in Paris), we calculate an emissions budget range for the OECD, and subsequently for the EU. For the EU to make its minimum "fair" contribution to the Paris "*well below 2°C*" commitment, its post-2017 energy-only carbon budgets should be between 23 and 32GtCO$_2$, or approximately six to nine years of current EU energy-only emissions. This conclusion depends on a successful and highly ambitious mitigation agenda for non-OECD nations, far beyond their respective Nationally Determined Contributions (NDCs).

For the EU to deliver on its share of a 2°C commitment it needs to begin an immediate programme of profound mitigation at a minimum rate of 12% p.a. in absolute emissions. Any delay in starting, or in pursuing a rate below 12% p.a., will either put a "likely" chance of 2°C beyond reach or require still more fundamental mitigation over the following years (see Appendix A). This level of mitigation is far beyond the EU's headline Nationally Determined Contribution target of a 40% reduction in emissions by 2030. The EU's current position essentially ignores any reasonable interpretation of equity and is informed by scenarios that assume the huge uptake of NETs and the direct removal of many 100s of billions of tonnes of carbon dioxide directly from the atmosphere. In addition, emissions arising from the EU's international aviation and shipping sectors are also excluded from the inventory used to estimate its mitigation commitments.

It is in this context that we have reviewed the climate change impact of natural gas production, distribution and consumption. In addition to CO$_2$, there are also warming effects from non-CO$_2$ greenhouse gases, of which methane is the most important. It currently contributes approximately 20% of the anthropogenic warming impact on the climate and increases in atmospheric methane concentrations have been observed since 2006, as well as regional increases in emissions. Both methane emissions and atmospheric concentrations are observed at the top end of Intergovernmental Panel on Climate Change (IPCC) scenarios. There is not yet consensus on the dominant causes of the rise in atmospheric concentration or the relative proportion attributable to the fossil fuel industry. However, a number of recent empirical studies have found official inventories of fossil fuel emissions reported by governments to be underestimates for the regions they addressed.

Measurement campaigns in the USA have identified discrepancies between "top-down" atmospheric methods of quantifying emissions and official inventories of emissions based on "bottom–up" methods. It appears that methane emissions from the natural gas supply chain are dominated by low numbers of high intensity assets or events, making representative sampling difficult. Consequently, there are justifiably large ranges in the potential estimates for general gas supply chain types.

Carbon dioxide is the dominant contributor to the climate change impact arising from natural gas production, distribution and consumption. In the short term and for a unit of emissions released at a given point in time, methane has a much greater warming effect than carbon dioxide. However, relative to CO_2, methane is quickly removed from the atmosphere via natural processes, and hence the warming from any pulse of methane diminishes within a few decades. Persistently high emissions of methane will of course replenish this loss and maintain the initial warming effect. The production and distribution of natural gas releases methane, deliberately and inadvertently, although the exact amount varies widely across locations, production technologies, and through time at a given location. Whilst leakage rates affect the relative contribution of methane to the climate change impact of natural gas supply chains, the long-term temperature change arising from any given quantity of production is dominated by CO_2 emissions as they persist in the atmosphere for thousands of years.

The anticipated increase in the production and shipping of liquefied natural gas (LNG) entails additional energy intensive steps to those associated with piped natural gas, adding a further CO_2 burden. Median estimates of supply chain emissions from LNG supply chains are nearly double those of average pipeline supply chains. Long distance pipelines, e.g. from Russia, may have higher emissions but these are poorly characterised at present. If methane leakage persists at current rates, and natural gas assets are constructed without consideration of their imminent retirement, then there will be both increased near term and increased long-term warming relative to a direct transition to a genuinely low carbon infrastructure.

The Paris 2°C and equity commitments, buttressed with the IPCC's carbon budgets, demand a minimum reduction in EU energy-only carbon emissions of around 95% by 2035 (c.f. 2015), with absolute decarbonisation of its energy system a decade later. In this context and assuming an immediate 12% p.a. mitigation path, (or accelerated mitigation to around 18% by 2023; see Appendix A), there is categorically no role for bringing additional fossil fuel reserves, including gas, into production. This conclusion is not significantly affected by the prospect of carbon capture and storage, where the limitations on deployment rates and likely upstream methane emissions substantially restrict its potential, even with a conservative reading of the Paris 2°C commitment, a rejection of 1.5°C and a weak interpretation of equity.

Considering both carbon dioxide and methane emissions, an urgent programme to phase out existing natural gas and other fossil fuel use across the EU is an imperative of any scientifically informed and equity-based policies designed to deliver on the Paris Agreement.

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Appendix A: Illustrative EU emission pathways consistent with the report's EU carbon budgets
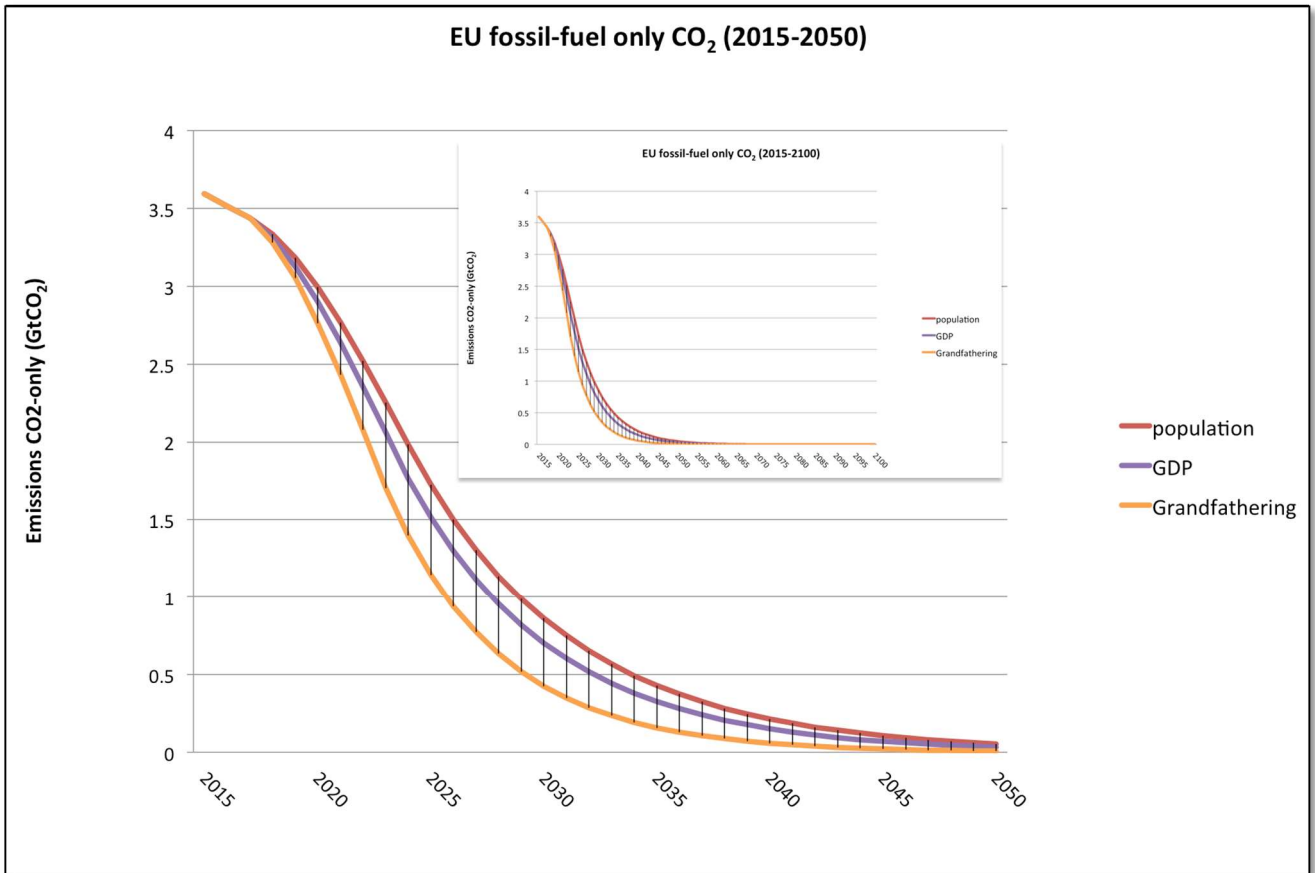

Figure 10. Illustrative EU emission pathways consistent with the report's EU carbon budgets. Inset shows the same pathways but on a 2015 to 2100 timescale

The above EU emission pathways are based on the 'EU mid-value CO_2 budgets' in Table 1, which in themselves assume a hugely challenging aggregate peak in emissions for the non-OECD nations occurring between 2022 and 2023 with their subsequent mitigation ratcheting up to 10% p.a. by 2045. If EU emissions were to continue at current rates, the EU energy-only carbon budgets would be exceeded within 6 to 9 years.

The EU pathways all assume an incremental annual increase in EU mitigation rates from 2017 to a maximum of 13% each year by 2025 for Population-based apportionment (32 $GtCO_2$); 14.25% p.a. by 2024 for GDP-based apportionment (29 $GtCO_2$) and 18% p.a. by 2023 for grandfather-based apportionment (23 $GtCO_2$). Thereafter each pathway continues at its respective maximum mitigation rate every year through until the virtual elimination of all EU CO_2 emissions from energy (i.e. across all sectors, including international aviation and shipping). A 95% reduction (c.f. 2015 – including aviation and shipping) occurs between 2035 and 2040 with a 99% reduction following around a decade later.

Appendix B: Emissions Estimates

Table 7 Reviews and Sectoral Studies

Reviews and Sectoral Studies			Total supply chain CO2 and methane emissions as a percentage of end use combustion CO2[24]					
Study	*Supply chain scope*	*Geographic scope*	*Lower*	*Central*	*Upper*	*%CH4 emissions / %CH4 extracted for Central estimate*	*Range definition*	*Method*
Balcombe et al (2016). Constrained estimates	Complete, exc LNG	Global	7%	22%	88%	0.97	Median, ± constrained range	Review and harmonisation of previous studies
Balcombe et al (2016). Constrained estimates	Complete, inc LNG	Global	16%	44%	134%	1.4	Median, ± constrained range	Review and harmonisation of previous studies
Allen et al 2013	Natural gas production	USA	3%	4%	5%	0.42	Mean ± 95% CI	Measurements at 190 volunteer sites, plus some EPA data
Zavala-Araiza et al (2015)	Natural gas production	Barnett Shale, USA	12%	15%	19%	1.5	Mean ± 95% CI	Bottom-up and top-down for same region. Airborne CRDS from Karion et al (2015), ground level Lan et al (2015)
Littlefield et al (2017)	Complete	USA	13%	17%	22%	1.7	Mean ± 95% CI	Bottom-up Monte Carlo analysis. Data from Allen et al (2013, 2014a, 2014b), Lamb et al (2015), Marchese et al (2015), Zimmerle et al (2015)

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[24] Combustion CO2 emissions taken as 48.4 gCO2/MJ HHV

Table 8 Examples of major EU supply chains

Examples of major EU supply chains			Total supply chain CO2 and methane emissions as a percentage of end use combustion CO2				
Study	*Supply chain scope*	*Geographic scope*	*Lower*	*Central*	*Upper*	*Range definition*	*Method*
Stamford and Azapagic (2012)	Complete	Offshore - North Sea		21%		Mean	LCA model from secondary data
Stamford and Azapagic (2012)	Complete	LNG - Algeria		46%		Mean	LCA model from secondary data
Stamford and Azapagic (2012)	Complete	LNG - Qatar		53%		Mean	LCA model from secondary data
Exergia (2015)	Complete	Norway		26%		Mean	LCA model from secondary data
Exergia (2015)	Complete	Algeria		53%		Mean	LCA model from secondary data
Exergia (2015)	Complete	Russia	70%	76%	83%	Mean ± 1 SD	LCA model from secondary data, Monte Carlo analysis for uncertainty
Exergia (2015)	Complete	LNG - Qatar	41%	42%	43%	Mean ± 1 SD	LCA model from secondary data, Monte Carlo analysis for uncertainty
MacKay and Stone (2013)	Production to entry onto transmission system	EU Conventional	7%		13%	Mean ± 1 SD	Survey of academic and policy literature
MacKay and Stone (2013)	Production to entry onto transmission system	Non-EU pipeline	33%		62%	Mean ± 1 SD	Survey of academic and policy literature
Tagliaferri et al (2017)	Production to entry onto distribution system	LNG - Qatar		36%			LCA model from secondary data
Safaei et al (2015)	Production to entry onto distribution system	LNG - Nigeria	31%	35%	57%	Mean - 90% CI, + max venting	LCA model from secondary data

Table 9 Unconventional resources

Unconventional resources			Total supply chain CO2 and methane emissions as a percentage of end use combustion CO2				
Study	*Supply chain scope*	*Geographic scope*	*Lower*	*Central*	*Upper*	*Range definition*	*Method*
MacKay and Stone (2013)	Production to entry onto transmission system	Shale gas - UK (prospective)	8%		49%	Mean ± 1 SD	Own calculations derived from academic and policy sources
Stamford and Azapagic (2014)	Complete	Shale gas - UK	24%	39%	232%	Mean ± full range from model	LCA model from secondary data
Heath et al (2014)	Complete	Conventional - US	23%	32%	90%	Median ± full range	Review and harmonisation of previous studies
Heath et al (2014)	Complete	Shale gas - US	28%	38%	119%	Median ± full range	Review and harmonisation of previous studies

NB *Estimates presented in Table 10 and Table 11 are for methane emissions only and do not include the CO2 emissions from the energy required at each stage, nor from end use combustion.*

Table 10 Top-down regional studies

Top-down regional studies			Total supply chain methane emissions as a percentage of end use combustion CO2						
Study	*Supply chain scope*	*Geographic scope*	*Lower*	*Central*	*Upper*	*%CH4 emissions / %CH4 extracted for Central estimate*	*Range definition*	*Method*	*Other notes*
Peischl et al (2016)	Geographic: exploration to transmission, mixed oil and gas	Bakken, USA	42%	62%	83%	6.3	Mean ± 1 SD	Airborne CRDS + mass balance	C2H6 ratio suggests gas production source
Petron et al (2014)	Geographic: exploration to transmission, mixed oil and gas	Denver-Julesburg Basin, USA	26%	41%	55%	4.1	Mean ± 1 SD	Airborne CRDS + mass balance	Allocates all fossil fuel production emissions to gas.
Peischl et al (2015)	Geographic: exploration to transmission, predominantly shale gas	Haynesville, USA	10%	15%	21%	1.1	Mean ± 1 SD	Airborne CRDS + mass balance	Allocates all fossil fuel production emissions to gas.
		Fayetteville, USA	10%	19%	28%			Airborne CRDS + mass balance	
		Marcellus Shale, USA	2%	3%	4%			Airborne CRDS + mass balance	
Caulton et al (2014)	Geographic: exploration to transmission, mixed oil and gas	Marcellus Shale, USA	28%		171%		Mean ± 1 SD	Airborne CRDS + mass balance	2 days only, may not be generalisable.
Karion et al (2013)	Geographic: exploration to transmission, mixed oil and gas	Uintah Basin, USA	61%	89%	116%	8.9	Mean ± 1 SD	Airborne measurements + mass balance	1 day only, may not be generalisable.
Petron et al (2012)	Geographic: exploration to transmission, mixed oil and gas	Denver-Julesburg Basin, USA	23%	40%	76%	4.0	Low, mean and high estimates according to	Static tower sampling + ground level mobile CRDS	

							scenario assumptions		
Ren et al (2017)	Geographic: exploration to transmission, mixed oil and gas	Marcellus Shale, USA	15%	39%	62%	3.9	Mean ± error limits	Airborne CRDS + mass balance	Ethane ratio suggests substantial coal source of methane, either coal production of O&G wells drilled through coal seams

Table 11 Bottom-up, site or process specific studies

Bottom-up, site or process specific studies			Total supply chain methane emissions as a percentage of end use combustion CO2					
Study	*Supply chain scope*	*Geographic scope*	*Lower*	*Central*	*Upper*	*%CH4 emissions / %CH4 extracted for Central estimate*	*Range definition*	*Method*
Omara et al (2016)	Production site specific	Marcellus Shale, USA	10%	14%	20%	1.4	Mean ± 95% CI	Ground level mobile CRDS
Marchese et al (2016)	Gathering and processing specific	USA	4%	5%	4%	0.5	Mean ± 95% CI	Ground level CRDS and QC-TILDAS sampling
Zimmerle et al (2015)	Transmission and storage system	USA	3%	3%	4%	0.4	Mean ± 95% CI	Ground level high flow sampling. Data from Subramanian et al (2015) measurements.
Lechtenbomer et al (2007)	Transmission system	Russia	5%	6%	15%	0.6	Mean ± 95% CI	Direct sampling of leaks at 5 compressor stations and pipelines (2003)
Lavoie et al (2017)	Refineries and power plant specific	USA	1%		4%	0.5	± 95% CI	Ground level sampling
Lamb et al (2015)	Distribution system	USA	1%		2%		± 95% CI	Ground level high flow sampling
McKain et al (2015)	Distribution system	USA	21%	27%	33%	2.6	Mean ± 95% CI	Continuous ground level sampling CRDS