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POST EXAMINATION CONSULTATION 3 SUBMISSION

I am a retired scientist and environmental consultant, working at the intersection of science, policy, and law, particularly relating to ecology and climate change. I work at a consultancy called Climate Emergency Policy and Planning (CEPP).

In so far as the facts in this statement are within my knowledge, they are true. In so far as the facts in this statement are not within my direct knowledge, they are true to the best of my knowledge and belief.

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1 INTRODUCTION

1.1 Post Examination Consultation 3

- 1 I am responding to the letter from David Wagstaff OBE, Deputy Director, Energy Infrastructure Planning Delivery (Department of Energy Security and Net Zero, DESNZ) of May 16th 2023. As an Interested Party at the DCO examination, I provide comments below on :

(A) Methane supply chain emissions. Particularly a recent scientific paper on the likely substantial underestimation of reported methane emissions from United Kingdom upstream oil and gas activities. This is important for the whole life cycle GHG emissions from the Net Zero Teesside Project. I submit (and have previously submitted) that no quantification and no assessment of methane supply chain emissions has been made in the scheme Environmental Impact Assessment, and that this renders the application unlawful.

The recent paper now suggests that the methane supply chain emissions are higher than previously thought. This is relevant to considerations of the Powering Up Britain strategy (and the Carbon Budget Delivery Plan), and Draft National Policy Statements, as detailed in this submission, and so relates to paragraph 9 of Mr Wagstaff’s letter.

(B) Further comments on the publication of the Powering Up Britain strategy as highlighted in paragraph 9 of Mr Wagstaff’s letter.

2 RECENT SCIENTIFIC PAPER SINCE EXAMINATION CLOSED

- 2 Early in 2023, the Royal Society of Chemistry journal *Energy & Environmental Science* published a paper¹ (“**RSC paper**”) on the likely substantial underestimation of reported methane emissions from United Kingdom upstream oil and gas activities. The paper is reproduced in full in Appendix A.
- 3 The paper found that the total UK methane CH₄ emissions from flaring, combustion, processing, venting, and Oil & Gas transfer to be 289 Gg CH₄ (0.72% of production). This figure is five times larger than the estimate from United Kingdom (UK) government’s National Atmospheric Emissions Inventory (NAEI) is used to provide UK greenhouse gas emission data to the United Nations Framework Convention on Climate Change. NAEI estimated the equivalent figure for 2019 to be 52 Gg CH₄, corresponding to the loss of 0.14% of gas production. The paper stated, “*The difference between current estimates used by NAEI and our estimates, which use more recent research findings, strongly suggests that the current*”

¹ Stuart N. Riddick, Denise L. Mauzerall. Likely substantial underestimation of reported methane emissions from United Kingdom upstream oil and gas activities. *Energy & Environmental Science*, 2023; 16 (1): 295 DOI: 10.1039/d2ee03072a

methods of compiling national GHG inventories in the UK, and likely elsewhere, are outdated (oldest EF derived in 1982) and systematically underestimate emissions.”

2.1 Why is the RSC paper important?

- 4 My written representation [REP2-061] highlighted from the outset of the examination concerns about the upstream methane leakage emissions, and that they had not been included in the Environmental Impact Assessment. In particular:
- A. I submitted that Environmental Statement (ES) had underestimated the Climate Change impacts of the NZT CCGT power station as no full lifecycle GHG assessment had been done. Quantifying and assessing upstream methane emissions was necessary for a full lifecycle GHG assessment, but emissions from upstream sources had not been included in the ES.
 - B. The applicant had calculated (assuming 90% combustion CO₂ capture) that the carbon intensity of the CCGT power station would be 41.2 tonnes CO₂e/GWh. However, this calculation assumed that methane supply chain emissions were 0.00% (ie zero - as methane leakage was not included in the EIA). I provided calculations, which are not disputed by the applicant, and which also assumed 90% combustion CO₂ capture, that showed that the carbon intensity would be 66.97 tCO₂e/GWh at 0.2% methane supply chain emissions, and 105.67 tCO₂e/GWh at 0.5% methane supply chain emissions.
 - C. I also raised concerns about the stability of gas supply chains for the UK and increased UK use of LNG from lax methane regulatory regimes which could lead to higher carbon intensities than 105.67 tCO₂e/GWh.
 - D. Critically, I wrote in [REP2-061] *‘The Environmental Statement has failed to comply with the Environmental Impact Assessment Regulations as it has not described all the likely significant effects on the environmental factor of greenhouse gas emissions including the “**direct effects and any indirect, secondary, cumulative, transboundary, short-term, medium-term and long-term, permanent and temporary, positive and negative effects of the development**” (EIA Regs Schedule 4 (5)). In excluding consideration of methane, the Applicant has not described how the gas power station will actually operate, and what its environmental impacts will be.’*
- 5 At 0.72% methane supply chain emissions (as per the RSC paper), the CCGT power station carbon intensity is 134.05 tCO₂e/GWh assuming 90% carbon capture rate. This is over 225% more than the carbon intensity reported by the applicant. The latest, and more scientifically accurate data on methane leakage, reinforces my concerns that the Applicant’s Environmental Statement has not described, nor assessed, how the power station will actually operate, and therefore the ES is not legitimate with respect to the EIA regulations.

- 6 It is important to note the impacts in terms of absolute GHGs (as tonnes CO₂ equivalents) from the methane supply chain emissions. I have adapted my WR, REP2-061, Table 1, below to show the annual methane supply chain emissions as a percentage of the CDBP 6th carbon budget (6CB) average annual residual emissions for the Power sector² (8.4MtCO₂e). Columns A, B, C, D and E present calculations for the NZT scheme at methane supply chain emissions in the range 0, 0.2% to 8%³ as per my original REP2-061, Table 1. A new column “RSC-paper” has been added for the 0.72% of methane leakage in production published in the recent paper.
- 7 Given the recent RCS paper and its explanation that the NAEI data which forms the basis of existing emissions factors is based on outdated methods which systematically underestimate emissions, I submit that the Secretary of State must assume that the best possible estimate of supply chain methane emissions must now be 0.72%, as in the RSC paper column below, and the worst case is unknown.
- 8 Based on the RSC paper, supply chain methane emissions for the NZS facility are over 6% of the 6CB average annual residual emissions for the Power sector, as below.

From ES Table 21-10	A	B	C	RSC-paper	D	E
Annual Operating Hours	8,424	8,424	8,424	8,424	8,424	8,424
Methane supply chain emissions %		0.20%	0.50%	0.72%	1.00%	8.00%
Methane hourly equivalent GWP20 (kg CO₂e)		17,649	44,124	63,538	88,247	705,980
Total Unabated emissions per hour (kg CO₂e)	281,547	299,196	325,671	345,085	369,794	987,527
Annual Total unabated emissions (tCO₂e)	2,371,752	2,520,431	2,743,450	2,906,998	3,115,149	8,318,927
Annual Total unabated emissions as percentage of CDBP 6CB average annual residual emissions (8.4MtCO₂e)	28%	30%	33%	35%	37%	99%
Annual methane supply chain emissions (tCO₂e)		148,680	371,699	535,246	743,397	5,947,175
Annual methane supply chain emissions as Percentage of CDBP 6CB average annual residual emissions (8.4MtCO₂e)	0.00%	1.77%	4.42%	6.37%	8.85%	70.80%

Table 1 – Adaption of REP2-061, Table 1 showing RCS paper methane supply chain emissions data and the impact of methane leakage on Carbon Budget Delivery Plan 6CB

² Table 2 of the CDBP (page 13) gives the Power sector residual emissions at 42 MtCO₂e for the 6th carbon budget, or an average of 8.4 MtCO₂e per year between 2033 and 2037.

³ These were selected to correspond to the range in the Bauer paper “On the climate impacts of blue hydrogen production” provided as Appendix B of my WR [REP2-061]

2.2 Related issues unresolved from the examination

9 The Applicant unambiguously stated in REP3-012 that only the direct impacts of GHGs (ie from the Combined Cycle Gas Turbine (CCGT) combustion process) had been provided in the ES. Indirect, secondary, cumulative, transboundary, short-term, medium-term, and long-term, permanent, and temporary, positive and negative effects had not been considered. In particular, the Applicant conceded that *“Upstream emissions associated with the supply of the gas were not included in the ES assessment”*.

10 In responding to my WR [REP2-061], the Applicant wrote in [REP3-012] that it would include a quantification and assessment of the upstream methane emissions at Deadline 5:

“An updated assessment of GHG emissions applying the updated IEMA Guidance (February 2022) and including the BEIS/Defra emissions factors will be submitted at Deadline 5 (2nd August 2022 to confirm this position).”

11 Note that the BEIS/Defra emissions factors are based on the NAEI estimates and methods which have now been found to significantly underestimate methane supply chain emissions.

12 However, despite the Applicant’s commitment made to the parties at the examination, and to the ExA, to provide an updated assessment of GHG emissions (albeit based on the seriously erroneous NAEI methods), I can find no evidence that the commitment was ever fulfilled. My concerns over whether the revised GHG assessment had been submitted by the Applicant, and the legitimacy of the ES, were recorded in my final submission at deadline D13 [REP13-022] at the close of the examination:

“To my knowledge, no updated assessment of GHG emissions was submitted at Deadline D5, or at any other deadline up to and including Deadline D12. I have searched thoroughly for such an update through the examination library and have not been able to find it.

...

It is not a matter of second-guessing what the significance might be, if an assessment compliant with the 2017 regulations were to be carried out, as the Applicant attempts to do in REP3-012, and then deciding that providing such an assessment is not necessary, as appears to be the case as the GHG assessment has not been updated. The law is that the ES must contain a description of the likely significant effects of the development including all those listed in Schedule 4.

As this has not been done, the ES, and the GHG description and assessment within it is unlawful.

The Secretary of State is required to reach a reasoned conclusion on the significant effects of the proposed development on the environment under Regulation 21 of the

2017 Regulations and s/he is unable to do so given that the ES is, inadequate and, unlawful with respect to the GHG description and assessment within it.”

2.3 Draft National Policy Statements

13 I can find no reference to supply chain methane emissions in the five draft Energy NPSs which suggest that DESNZ has not properly considered the very significant issues which pertain to them, nor is aware of the latest science in the RCS paper.

14 With respect to the absence of quantification and assessment of the supply chain methane emission the NZT ES, the Energy NPS would support my case that this does not comply with the EIA Regulations. Under section 4 “Assessment Principles” and section 4.2 “Environmental Principles”, EN-1 states:

“The Regulations require an assessment of the likely significant effects of the proposed project on the environment, covering the direct effects and any indirect, secondary, cumulative, transboundary, short, medium, and long-term, permanent and temporary, positive and negative effects at all stages of the project, and also of the measures envisaged for avoiding or mitigating significant adverse effects.”

15 At 4.2.10, draft EN-1 states:

“The applicant must provide information proportionate to the scale of the project, ensuring the information is sufficient to meet the requirements of the EIA Regulations.”

16 I submit that the (best case) methane supply chain emissions from this single scheme that consume over 6% of the CBDP Power sector residual emissions in the 6CB, and that is very significant. The proportionate information that draft EN-1 requires can be no less than a full quantification and assessment of these emissions in the ES. This has not been done by the Applicant.

3 POWERING UP BRITAIN STRATEGY

3.1 Background: the revised Net Zero Strategy (NZS)

17 The Government laid the NZS before Parliament on 19 October 2021 as a report under section 14 of the Climate Change Act (CCA) 2008. The strategy was intended to fulfil the duty, at section 13 of CCA 2008, to “prepare such proposals and policies” that will enable the carbon budgets under the CCA 2008 to be met. The NZS was subsequently found to be unlawful in July 2022, and the Government was ordered to lay before Parliament a fresh report under section 14 before the end of March 2023. The Government published an array of reports including “Powering Up Britain” (PUB) and the “Carbon Budget Delivery Plan” (CBDP) as part of a revised NZS at the end of March 2023.

18 In relation to securing the NZS, I highlight here what the Court said in the NZS judgment⁴ on delivery risk and policy gap. Holgate J. recorded the NZS’s acknowledgement that the delivery pathways to achieve the 6th Carbon Budget are highly ambitious and face considerable delivery challenges and recorded that achievement was subject to a wide uncertainty range. The judge noted at paragraphs 204 and 211 that in approving the Net Zero Strategy, “*one obviously material consideration which the Secretary of State must take into account is risk to the delivery of individual proposals and policies and to the achievement of the carbon budgets and the 2050 net zero target.*” In finding the NZS unlawful, the judge described risk to delivery as the critical issue when concluding that the information provided to the Minister when reporting on the NZS was insufficient to enable him to discharge his reporting obligations under section 14 of the Climate Change Act 2008.

19 Below, I will provide evidence on the new PUB and CBDP policy documents, and the relevance of them to GHG emissions are dealt with for NZT project.

3.2 Power sector modelling in the PUB and CBDP

20 Appendix B of the CBDP at paragraph 7 (page 21) under the heading “*Explanation of power policies represented by a single emissions figure*” states:

“DESNZ simulates the power sector using the Dynamic Dispatch Model, with emissions savings determined by comparing indicative net zero consistent scenarios against a scenario where no further government action is taken to decarbonise the power sector (which does not need to be net zero compliant). For all scenarios, the model builds sufficient capacity to ensure security of supply, with the capacity mix balanced to keep system costs low. Although specific capacity mixes are required by these scenarios, DDM modelling has shown that there are a range of capacity mixes that can achieve net zero and the government has adopted a market driven approach to delivering net zero.”

21 The problem here is that the DDM is effectively a black-box and the detail of individual policies and proposals is hidden. By hiding the impacts of individual policies and proposals for the Power sector, the PUB (revised NZS) presentation immediately ignores Holgate, J’s clear position that an obviously material consideration is that Secretary of State must take into account is risk to the delivery of individual proposals and policies.

22 In terms of methane supply chain emissions, the modelling in the DDM will be based on NAEI data. However, the RSC paper now shows that the NAEI modelling is outdated and severely underestimates methane leakage in UK gas supply.

⁴ R (Friends of the Earth) v Secretary of State for Business Energy and Industrial Strategy [2022] EWHC 1841 (Admin)

23 Sector modelling for “Power” is described in the "Powering Up Britain Technical Annex" (PUBTA), pages 21 to 31. Methane leakage is not covered, although Power CCUS is mentioned at the bottom of page 25 in the context of Dispatchable Power Agreements (DPA).

24 At Appendix D (“Sectoral summaries of delivery confidence”) of the CBDP, moving from unabated gas is discussed at paragraph 7 (page 174), and says, “*Reducing emissions in the power sector will also depend on bringing forward flexible technologies that are capable of replicating the role of unabated gas in the electricity system*” and states power CCUS being one of the technologies considered.

25 The problem here for the applicant for NZT (a power CCUS system) is that there is no evidence that the risks to delivery of the power sector emissions trajectories from underestimates of methane supply chain emissions (now demonstrated by the RSC paper) have been considered. This is, further, a problem for the Secretary of State in deciding whether to approve the scheme as the ES contains no information of methane supply chain emissions, was not updated to do so, and now there is recent scientific evidence that the methane leakage issue with UK supplied gas is much greater than previously assumed (and accounted for by national NAEI data sets).

26 The risk analysis of delivery of the required emissions savings simply has not been done despite paragraph 7⁵ appearing under “Risks and mitigation”. Further, the black-box nature of the DDM makes it impossible from the information in the CBDP and PUBTA to determine the risks.

3.3 NZT in the PUB and CBDP

27 However, it is possible to get an indicative quantification of the impact of the underestimate of methane leakage as it relates to the NZT project within the PUB and CBDP from Table 1 above.

28 By background, Table 2 of the CBDP (page 13) gives the Power sector residual emissions at 42 MtCO₂e for the 6th carbon budget, or an average of 8.4 MtCO₂e per year between 2033 and 2037. So the average annual emissions space for the entire UK Power sector is 8.4 MtCO₂ between 2033 and 2037.

29 Table 1 above calculated that the supply chain methane emissions from the NZT project alone accounted for over 6% of CBDP 6CB average annual residual emissions (8.4MtCO₂e). I submit that this is a very serious level of emissions, not accounted for by the Applicant, and provides a serious risk to the staying within the Power sector residual emissions for the 6th Carbon budget, and therefore a risk to the overall delivery of the 6th carbon budget and the revised NZS.

⁵ Appendix D (“Sectoral summaries of delivery confidence”) of the CBDP, Page 174

- 30 Should supply chain methane leakages emissions be even higher because of a greater proportion of imported LNG and other sources of gas in the supply, then the percentage of residual emissions consumed becomes even higher.
- 31 It should further be noted that this is for just one power station, the NZT. However, it should be noted that the same issue applies to every other power CCUS station and also every other blue hydrogen facility⁶ planned. The Keadby 3 Carbon Capture Power Station was granted development consent on 7th December 2022 which will also consume the same order of best case percentage of 6CB average annual residual emissions (ie around 6%) for methane supply chain emissions based on the RCS paper.
- 32 The issues here are that upstream methane leakage for the NZT power station, and other planned methane based power systems, consumes a significant proportion of the 6CB power sector residual emissions. It does not appear that methane leakage, nor the cumulative effects of it across all power CCUS and blue H2 plants planned has been considered in the PUB, CBDP documents.
- 33 The PUB and CBDP is based on the complex DDM model which is effectively a black box. There is an urgent need to review the residual emissions for the 6CB against all the planned projects for power CCUS, power BECCS and blue hydrogen.
- 34 It is extremely unlikely that the projects being planned will fit into the available residual emissions for the Power sector in the 6CB. The Secretary of State is therefore unable to make a reasoned decision on the environmental impacts of the NZT scheme.
- 35 It is of great concern that there appears to be no risk assessment of supply chain methane emissions in the PUB and CBDP, despite these posing a very significant risk to delivery of the PUB (revised NZS) and the Court finding in the July 2022 that risk assessment of policy delivery is a critical material factor for the revised NZS.

4 DECISION MAKING FOR THE NZT

- 36 I now, respectfully, write as if directly to the SoS although through this consultation process. I request that the SoS considers all the above points, and also the following, in his/her decision making.
- 37 Over 6% of PUB (revised NZS) power sector emissions is a very serious level of emissions to come from methane leakage on a single project, the NZT. It has not been accounted for by the Applicant, and provides a serious risk to the staying within the Power sector residual emissions for the 6th Carbon budget, and therefore a risk to the overall delivery of the 6th carbon budget and the revised NZS.

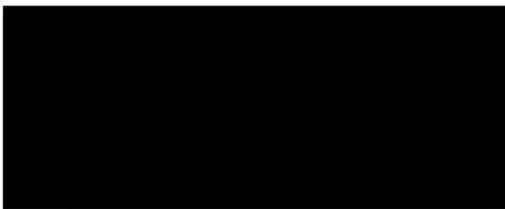
⁶ See the Bauer “On the climate impacts of blue hydrogen production” provided as Appendix B of my WR [REP2-061]

38 The combined evidence above on the likely scale of supply chain methane emissions (cumulative across planned methane based power systems) and their impact on the revised NZS (PUB and CBDP) shows that there can be no confidence that delivery of this critical climate strategy under the Climate Change Act 2008 is secured. In fact, the evidence strongly supports the opposite case that the revised NZS is unlikely to be delivered successfully, and, in any case, the risks to delivery have not been adequately assessed.

39 As well as taking this into account, at the time of his/her decision, the SoS should consider the latest evidence on the revised NZS, the status of any on-going legal challenge to it, and my submissions here (by which I respectfully mean that this submission should be made available to the SoS to consider personally).

40 Overall, I submit that the Secretary of State cannot lawfully approve the NZT scheme given the recent science on the level of supply chain methane emissions, and the lack of environmental assessment of these emissions by the Applicant.

5 SIGNED

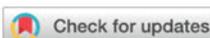


Dr Andrew Boswell,
Climate Emergency Policy and Planning, May 30th, 2023

6 APPENDIX A: RCS PAPER

Journal Reference:

Stuart N. Riddick, Denise L. Mauzerall. Likely substantial underestimation of reported methane emissions from United Kingdom upstream oil and gas activities. *Energy & Environmental Science*, 2023; 16 (1): 295 DOI: 10.1039/d2ee03072a

Cite this: *Energy Environ. Sci.*,
2023, 16, 295Likely substantial underestimation of reported
methane emissions from United Kingdom
upstream oil and gas activities†Stuart N. Riddick *^{ab} and Denise L. Mauzerall ^{bc}

The United Kingdom (UK) government's National Atmospheric Emissions Inventory (NAEI) is used to provide UK greenhouse gas emission data to the United Nations Framework Convention on Climate Change. The NAEI bottom-up approach estimated 2019 methane (CH₄) emissions from the extraction and transport of oil and natural gas (O&G) from offshore sources to onshore terminals at 52 Gg CH₄, corresponding to the loss of 0.14% of gas production. Here we investigate the approaches used by the NAEI and find it substantially underestimates leakage. We suggest alternative integrated approaches that combine direct measurements, management practices, and the effects of environmental conditions to estimate fugitive emissions. We estimate the total UK CH₄ emissions from flaring, combustion, processing, venting, and O&G transfer to be 289 Gg CH₄ (0.72% of production) five times larger than the NAEI estimate. We suggest NAEI underestimates emissions because of outdated/incorrect emission factors, incomplete activity data, and incomplete data on vented emissions. Similarly, CH₄ emissions from upstream O&G in other countries may be underestimated, with regional regulatory differences resulting in venting often being a substantially underestimated emission source. While bottom-up methods can be used to understand the relative size of emissions from the extraction and transport of O&G, they are inherently biased low as they only include emissions from processes and activities designated as emission sources and for which emission factors exist. Emission factors remain a large source of uncertainty as many used to generate the NAEI inventory are taken from industrial studies or unpublished research that have not been independently validated. To improve the NAEI estimate, widespread and frequent direct measurements are needed to supplement and improve bottom-up emission estimates generated with existing emission factors and activity levels.

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Broader context

Accurate quantification of methane emissions is important as it is a strong greenhouse gas and contributes to production of tropospheric ozone, which is damaging to human health, ecosystems and agriculture. In general, greenhouse gas inventories are generated using activity data and emission factors. The UK government currently estimates 0.13% of the methane extracted from offshore activities is lost before it reaches land. These emission estimates are reported to the Intergovernmental Panel on Climate Change (IPCC), the United Nations Economic Commission for Europe (UNECE) and the United Nations Framework Convention on Climate Change and used to better understand the drivers of climate change. Recent studies suggest that emission factors currently used for inventory development may not accurately represent emissions over the full range of actual environmental conditions and management practices and that some emitting activities are not reported. Hence, emissions may be much higher than currently reported. Here we reassess methane lost from extraction and transport of natural gas in the UK and globally. We critically evaluate current methods, addressing their shortcomings, and provide methodologies and recalculations which indicate five times more methane is leaked from upstream oil and gas processes in the UK than is indicated in the NAEI.

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1. Introduction

In 2019, natural gas (NG) supplied 41% of the United Kingdom's (UK's) total energy demands,¹ with 50% coming from UK offshore oil and gas (O&G) operations and 50% imported either using pipelines or liquified NG, including imports from Norway (30%), Qatar (9%), USA (3%), Russia (3%) and the Netherlands

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(2%).² Many recent studies have shown that methane (CH_4) is lost during extraction and transport of O&G.^{3–6} Leakage of CH_4 is important as it is a strong greenhouse (GHG) gas ($\text{GWP}_{20} = 84$; $\text{GWP}_{100} = 28$), contributes to production of tropospheric ozone which is damaging to human health, ecosystems and agriculture,^{7,8} and is identified as a key target gas for reduction to meet climate goals.^{9,10} The UK is a participant in the Global Methane Pledge in which participating countries commit to reducing global CH_4 emissions by at least 30% from 2020 levels by 2030. Under this pledge the UK has committed to "...working to continuously improve the accuracy, transparency, consistency, comparability and completeness of [their] national greenhouse gas inventory reporting under the UNFCCC and Paris Agreement".¹¹ Here we investigate the UK National Atmospheric Emissions Inventory (NAEI) methodology and CH_4 leakage from upstream UK O&G production and transmission processes which primarily occur during offshore extraction and transport.

Currently, the UK government estimates 52 Gg year^{-1} (0.13%) of the 22 Tg year^{-1} CH_4 produced offshore by the UK is lost before it reaches land.² Emissions are estimated by each O&G operator for flaring, venting and offshore oil loading activities using activity data, typically the net energy production from each facility and emission factors (EFs). The emission estimates are then reported to the UK NAEI.¹² As part of the Paris Agreement,¹³ the UK publishes the NAEI to report anthropogenic GHG emissions to the Intergovernmental Panel on Climate Change (IPCC), the United Nations Economic Commission for Europe (UNECE) and the United Nations Framework Convention on Climate Change.¹⁴

In 2019, 99.8% of UK O&G was produced offshore using 323 installations run by 29 different operators (Fig. 1). Of these, 257 were production platforms, where O&G was transported to the mainland by pipeline, and 66 were floating production storage and offloading (FPSO) installations.¹⁵ FPSOs extract O&G, process and store oil until it can be transported by tanker, and transfer gas to the UK by pipeline. The UK only extracts 0.2% of produced O&G onshore, primarily from a single site at Wytch Farm in Dorset.²

Typically, CH_4 emissions from upstream O&G operations reported to the IPCC or the UNECE are derived from bottom-up methods which use EFs for specific processes multiplied by those processes' activity levels.^{12,15,16} However, recent studies suggest that EFs currently used for inventory development may not accurately represent emissions over the full range of actual environmental conditions and management practices.^{10,17–20} These studies suggest that emissions are dynamic and can be affected by wind speed, temperature, atmospheric pressure, gas venting management and oil offloading strategies and frequency. In addition, some processes that emit CH_4 may be entirely missed. Thus, emissions can deviate substantially from those calculated from static EFs in bottom-up inventories like the NAEI. Overall, GHG emission estimates have the highest integrity when verified by direct, top-down atmospheric flux measurements.^{5,20–23}

Currently, the best strategy to directly measure emissions from offshore facilities is unclear. The US EPA's Other Test

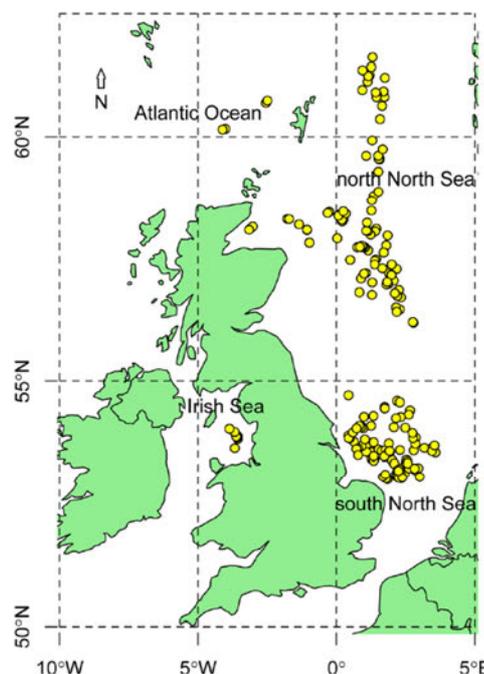


Fig. 1 Locations of all UK offshore oil/gas operations (yellow circles). Source: North Sea Transition Authority, 2021.

Method (OTM) 33A²⁴ is potentially confounded by the marine boundary layer and it is unclear if these traditional methods can be used to generate representative emission estimates.^{25,26} Tracer release methods are also commonly used to quantify site-wide emissions onshore,²⁷ however, the transportation and installation of the required compressed gas cylinders is a significant safety concern and is hence unlikely to be adopted by operators. Mass balance methods using drones²⁸ would avoid the micrometeorological issues presented to OTM33A and the safety concerns of tracer release, however drone mounted trace gas analysers (fixed wing or otherwise) cannot operate in strong winds and will be limited to fair weather measurements that would not inform the efficacy of the flare under adverse conditions. Satellites, such as the GHGSat instrument suite, are capable of observing site-wide emissions, however, satellites have difficulty with CH_4 retrievals over water.²⁹ Developments in remote sensing of CH_4 over water may improve in the future and research is already suggesting ways to overcome the over-water retrieval issues.^{30,31}

As technology and methodology for direct measurement of emissions from offshore facilities in the UK remains unproven, bottom-up methodology remains the best way of estimating emissions. However, the suitability of EFs used to derive the emissions remains unclear. In this study we reassess the CH_4 loss from extraction and transport of O&G within the UK. This study only estimates losses from offshore extraction in the UK and from UK high-pressure transmission networks and does

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not estimate emissions from onshore, extraction in other countries or from low-pressure distribution networks. Our aim is to critically evaluate current bottom-up methods of estimating upstream UK CH₄ emissions, address their shortcomings, and provide methodologies and recalculations of the estimates as necessary.

2. Upstream CH₄ leakage: processes, sources, NAEI estimates, and improved methods of estimation

2.1. Offshore oil and gas extraction processes

Offshore production platforms extract an oil/gas/water mixture from beneath the seabed and pass this mixture into separators, where gas is mostly separated from oil and water (Section S1 and Fig. S1, ESI†). Natural gas is transported to shore *via* the export line, oil is generally transported to shore *via* pipeline, while water is treated and then transferred back to the ocean. Ideally, all gas lost through is either recovered or sent to a flare. A full description of gas routing is given in Section S1 and Fig. S1 (ESI†).

2.2. Venting

Sources. A production platform vents NG for two primary reasons. (1) to control excessive pressures on drill boats when testing well performance; and (2) to vent excess gas during oil and gas processes on a production platform where gas recovery or flaring is not possible because the platform does not have suitable compressors (*i.e.* does not have vapor recovery units (VRUs)) or transport ability (*e.g.* pipelines to shore).

NAEI methodology. The EFs used to generate the NAEI emission rates are not explicitly presented in NAEI documents, but were found in the EMEP/EEA Air Pollutant Emission Inventory Guidebook.^{32,33} They appear to have been obtained from three unpublished and publicly unavailable sources written between 1992 and 1994 and based on facilities in the UK, Canada and Russia.^{34–36} We identified UK venting EFs of 270 and 498 Mg CH₄ facility⁻¹ for oil-only and combined O&G facilities³² resulting in NAEI emissions of 24.6 Gg CH₄³⁷ in 2019. Generally, a facility is defined as any floating or fixed platform structure that houses equipment used to extract hydrocarbons and transport them to storage facilities, transport vessels or pipelines to shore. As the primary sources of the EFs were unavailable, judging their quality is impossible.

Improved estimation technique. To improve the NAEI emission estimate for venting, we use the 2019 vented emissions reported to the North Sea Transition Authority (NSTA) by O&G operators (112 Gg CH₄).¹⁵ Typically, the volume of gas vented is measured using metering systems with an uncertainty of ±30% and the CH₄ content in NG can vary by ±6%.³² We therefore use the root sum square of these values, ±31%, as the uncertainty in the gas vented annually.

2.3. Flaring

Sources. As with vented emissions, some NG cannot be sent to the export pipelines and is instead sent to the flare on a

production platform. Flaring converts hydrocarbons in NG to carbon dioxide, a less potent GHG gas. We assume that all NG lost from condensate tank flashing, vapor recovery units (VRUs), dehydrators, water tanks and compressors is routed to the low pressure (LP) flare, while upset conditions (over pressure of the separators or VRU failure) result in gas being sent to the high pressure (HP) flare (Section S1 and Fig. S1, ESI†).

NAEI methodology. The NAEI EF, 0.011 Gg CH₄ Gg⁻¹ NG flared,³⁸ was used to calculate a flaring emission estimate of 15.6 Gg CH₄³⁷ in 2019. The NAEI EF is explicitly stated by the NAEI (Supplementary Material Table S1, ESI†), but does not appear in the EMEP document. Its heritage remains unknown³² and corresponds to a NG destruction efficiency (DE) of 0.989. The source of the activity data used to generate the flaring emission estimate is not reported in the NAEI database. The US EPA document referenced by the NAEI defines flare DE as 98% with an associated uncertainty of +2, -3%.³⁹ The US EPA DE was first calculated using measurements made downwind of onshore flares in Tulsa, OK, USA in 1982⁴⁰ and Detroit, MI, USA in 2010,⁴¹ both experiments were conducted in wind speeds less than 2 m s⁻¹. The average wind speed offshore in the UK in 2019 was 9.8 m s⁻¹,⁴² with 95% confidence intervals of 4 m s⁻¹ and 17 m s⁻¹.

Improved estimation technique. Research has reported that DE is likely influenced by the properties of the flare (*i.e.* flare gas temperature, gas flow rate, flare diameter, flare jet speed), the environmental conditions in which flaring takes place (*i.e.* wind velocity, precipitation, temperature, relative humidity, atmospheric pressure), gas composition details (*i.e.* CH₄, VOC, CO₂ and O₂ composition) and physical condition of the flare (*i.e.* age, corrosion by salt, injectors blocked by soot).^{43–48} Here we adopt an algorithm that considers how environmental conditions could affect the flare efficiency. We neglect the effect of varying flaring technology and infrastructure.

Published research on DE is limited⁴⁸ and is a field of research that has not been updated in 20 years. The only published, quantitative research on flare DE we could find, Johnson and Kostiuk (2002), used controlled NG emissions in a wind tunnel to generate empirical relationships between the cross-wind speed and DE. This study presents flare inefficiency (1-DE) as a function of the wind speed (u , m s⁻¹), flare gas exit velocity (v , m s⁻¹), acceleration due to gravity (g , m s⁻²), stack outside flare diameter (d , m) and lower heating value of CH₄ (LHV, MJ kg⁻¹) (eqn (1)).⁴⁸ Johnson and Kostiuk (2002) presented coefficients A and B specific to the type of gas being flared.

$$(1 - DE)(LHV)^3 = A \exp\left(\frac{B \cdot u}{(gvd)^3}\right) \quad (1)$$

Assuming: (1) flare DE is 0.98 at $u = 2$ m s⁻¹; (2) all other variables (v , g , d and LHV) in eqn (1) remain constant; (3) $A = 156.4$ (MJ kg⁻¹)³ and $B = 0.318$ for natural gas;⁴⁸ and (4) the average u offshore in the UK in 2019 was 9.8 m s⁻¹⁴² (95% CIs of 4 m s⁻¹ and 17 m s⁻¹), eqn (1) can be used to calculate an average DE of 0.905 (range 0.844 to 0.940).



2.4. Fugitive emissions - process and combustion emissions

Sources. We define fugitive emissions as CH₄ emitted from the process and combustion activities on a production platform during times of non-flaring and non-venting.

NAEI methodology. Fugitive emissions are presented in the NAEI as offshore fuel combustion emissions and offshore process emissions and estimated at 3.5 and 3.8 Gg CH₄ in 2019, respectively. NAEI combustion EFs are 2.4 and 0.18 kg CH₄ TJ⁻¹ of oil and NG produced, respectively.³⁸ It is unclear how these EFs have been generated; they seem to be derived from the IPCC Tier 1 EFs for stationary combustion in the energy industry for crude oil and NG of 3 (range 1 to 10) and 1 (0.3 to 3) kg CH₄ TJ⁻¹, respectively.¹⁴ The IPCC EFs were established using the expert judgement of inventory experts for the 1996 IPCC Guidelines and are still considered valid.¹⁴

Improved estimation technique. We estimate fugitive emissions from a typical offshore facility at 725 Mg CH₄ year⁻¹ from combustion (generators, export compressors) and processing (flash from the oil tanks, dehydrators and water treatment) activities. Total emissions include loss from power generation, export compressors, flash gas, dehydrators and water treatment. Facility power supply is typically provided by 50 MW NG turbines,^{50,51} gas slip from this type of gas turbine is estimated at 1.14 g CH₄ MWh^{-1.52} which results in emissions of 292 Mg CH₄ year⁻¹. Similarly, slip from ten 1000 hp export compressors is estimated at 58 Mg CH₄ year^{-1.52} Using the Vasquez-Beggs Solution gas/oil ratio correlation method,⁵³ flash gas from a facility producing 450 m³ oil day⁻¹ is estimated at 374 Mg CH₄ year⁻¹. Gas loss from glycol dehydrators is estimated at 276 scf CH₄ MMscf⁻¹ NG⁵⁴ resulting in an average facility producing 119 kg CH₄ year⁻¹. Gas loss from water treatment is estimated at 0.415 g CH₄ m⁻³ of produced water,⁵⁵ an average water production of 1590 m³ water per day¹⁵ results in emissions of 200 kg CH₄ year⁻¹. If the total 725 Mg CH₄ year⁻¹ is routed to LP flare (DE of 98%), total emissions from 323 facilities are estimated at 15 Gg CH₄ year⁻¹. While we acknowledge that the numbers used to generate these emissions are based on several assumptions (flare DE, size of generator, number of compressors, and amount of oil, water and gas produced), these ideal values are twice as large as the NAEI estimate and indicate NAEI may be underestimating emissions.

Direct measurement of CH₄ emissions from O&G production platforms in the North Sea estimated fugitive emissions during normal extraction operations of 0.19% of production, ranging from 0.04 to 1.41%.⁴ These emissions could have come from incomplete fuel combustion, equipment leaks or non-optimal operation on the working deck (turbines, engines, heaters, etc.).

2.5. Offshore oil loading

Sources. Floating production storage and offloading (FPSO) installations are slightly different from the ideal platform. These offshore facilities extract oil and other liquid hydrocarbons, process them offshore, and store them until they are offloaded to a tanker. Methane loss can occur when oil is transferred to a tanker and is a function of the CH₄ content in the oil, the movement of the vessels, and the temperature of the oil.³³

NAEI methodology. The EF used by the NAEI, 0.000018, was derived from operators' data, discussed at the United Kingdom Offshore Operators Association (UKOOA) Atmospheric Emissions Working Group and subsequently published as a UKOOA internal document in 1995.⁵⁶ This publication is not publicly available and the UKOOA did not respond when contacted about access. The 2019 NAEI estimate from offshore oil loading in the UK was 0.9 Gg.

It is unclear if the UK EF is representative. The CH₄ emissions from Norwegian oil loading in 2016 were estimated to be 1.95 Gg (or 10% of the total emissions from upstream O&G production),^{33,57} compared to 0.95 Gg from offshore oil loading in the UK (or 2.4% of the total CH₄ emissions from upstream O&G production). More information on the methods used to derive the current NAEI EF for offshore loading is needed to confirm or refute the apparent UK under/over-estimate of CH₄ emissions from this source.

Improved estimation technique. No direct measurement of CH₄ loss from offshore oil loading has been reported and, in the absence of peer-reviewed evidence, we present the US Environmental Protection Agency's approach as an alternative.⁵⁴ Based on an integrated measurement and modelling approach, the total loading loss of CH₄ (C_L , kg CH₄/103 gallons of oil loaded onto a shuttle tanker) is a function of the true vapor pressure of loaded crude oil, (P , psia), the molecular weight of vapours (M , g mol⁻¹), the vapor growth factor ($G = 1.02$), the temperature of vapours (T , °R) and the arrival EF (C_A , kg CH₄/103 gallons of oil loaded) (eqn (2)). This algorithm has been developed by the US EPA to estimate emissions for the loading of crude oil into ships and ocean barges.

$$C_L = C_A + 1.84(0.44P - 0.42) \frac{MG}{T} \quad (2)$$

Both P and T are temperature dependent and emissions are higher at higher temperatures, the average temperature in the North Sea varies from 5 to 15 °C. The value of C_A depends on the condition of the loading and ranges from 0.33 for a clean boat to 0.86 for an uncleaned ship that had a volatile previous cargo. Taking the values from the EPA document,⁵⁴ the average C_A is 0.199 kg CH₄/103 gallons of oil loaded, while at 5 °C C_A is 0.181 kg CH₄/103 gallons of oil loaded and at 15 °C is 0.457 kg CH₄/103 gallons of oil loaded into an uncleaned ship.

2.6. Natural gas transfer by high-pressure pipelines

Sources. In the UK, most NG is transported from offshore installations to gas terminals using a 45 000 km⁵⁸ long network of high-pressure transmission pipelines. Gas enters the national transmission network from which it either goes to the distribution network or is stored. Storage facilities include salt caverns, onshore LNG storage sites, and depleted onshore gas fields.⁵⁹

NAEI methodology. For 2019 the NAEI estimated CH₄ leakage from NG transmission at 3 Gg CH₄ corresponding to an EF of 103 kg CH₄ leaked Gg⁻¹ NG transported (0.01% loss of gas transported or 67 kg CH₄ km⁻¹ pipeline year⁻¹), assuming 29 000 Gg CH₄ was produced offshore in 2019.¹ This does not



account for the transportation of non-UK produced gas. The NAEI EF is claimed to derive from, but not equal to, the EMEP EF of 920 kg of CH₄ leaked Gg⁻¹ NG transported (0.092% or 600 kg CH₄ km⁻¹ pipeline year⁻¹), which is based on data from the Corinair 1990 database.³³

IPCC EFs for pipelines are 130, 1300 and 13 000 kg CH₄ km⁻¹ pipeline year⁻¹ for high, medium and low quality pipelines, taken from currently unpublished work by the International Gas Union, and based on data for a dozen countries including Russia and Algeria,¹⁴ and suggest the 1990 NAEI EF may be an underestimate. More recent studies estimate CH₄ loss from transmission pipelines in the US at between 0.07 and 0.8%,^{60,61} while CH₄ losses from Russian pipelines are estimated at 1.4%.^{62,63}

Updated estimation technique. To generate a representative emission estimate from NG transport from pipelines we will use the observations of Stephenson *et al.* (2011). This study was chosen as it was conducted in the US and the most analogous to the UK of the published studies.^{14,60-63} Stephenson *et al.* (2011) estimate the CH₄ losses from pipelines at 0.07% with an uncertainty range of ±23%.

3. Results

3.1. Reassessed 2019 emission inventory

We present our reassessed 2019 estimates for venting, flaring, fugitive emissions, offshore oil transfer and transfer by pipeline here and compare our estimates with the NAEI CH₄ leakage estimates (Table 1). Our estimated total emission for the 2019 upstream UK oil and gas production and transmission activities is 289 Gg CH₄ year⁻¹, with an uncertainty range of 112 to 1181 Gg CH₄ year⁻¹. The NAEI emission estimate for the same year was 52 Gg CH₄ year⁻¹.

3.1.1. Venting. Our 2019 CH₄ emissions estimate for offshore venting, as reported by NSTA, is 112 Gg CH₄ (range 78 to 146 Gg CH₄).¹⁵ The NSTA data suggests the NAEI currently underestimates vented CH₄ emissions (NAEI estimate 25 Gg CH₄ year⁻¹) and, as the NSTA data are reported by operators, it strongly suggests that the fixed EFs of 270 and 498 Mg CH₄ facility⁻¹ for oil and O&G facilities, respectively, do not adequately estimate vented emissions from modern offshore facilities. Venting is the largest source of offshore emissions in our reassessed estimate (Table 1).

3.1.2. Flaring. Using the destruction efficiency (DE), calculated by eqn (1), and data supplied by O&G operators,⁴⁸ our 2019 estimate for CH₄ emissions from offshore flaring is 74 Gg CH₄ (NAEI estimate 16 Gg CH₄ year⁻¹). Our estimate assumes all UK offshore installations' flares are optimally physically efficient, *i.e.* have not degraded with age, are not corroded by salt, injectors are not blocked by soot and gas/flame jet velocities are optimized.^{43,48} The DE of flares at O&G facilities have been reported by several studies. Onshore, Chambers *et al.* (2003) used a differential absorption LIDAR to calculate the DE from six flares in Alberta, Canada ranging from 0.55 to 0.98 with a mean DE of 0.84.⁴⁹ Offshore, aircraft measurements of facilities in the Gulf of Mexico flaring 150 MMscf d⁻¹ NG estimated a

Table 1 2019 methane emission estimates for upstream UK oil and gas production and transmission activities. Emissions reported in the UK National Atmospheric Emissions Inventory (NAEI) are compared with emissions calculated using the improved integrated approach detailed in this study. Emissions are presented as Gg CH₄ year⁻¹ and Loss as the % of production

Activity	NAEI Gg year ⁻¹	EF date	Improved approach Gg year ⁻¹	Source date
Venting	25 ^b	1992	112 (78–146) ^e	2020
Flaring	16 ^c	1982	74 (65–169) ^f	2002
Fugitive ^g	7 ^d	1996	76 (9–831) ^g	2020
Off. oil	1 ^b	1995	1 (1–2) ^h	2008
Pipeline	3 ^d	1990	26 (19–33) ^g	2012
Total emission	52		289 (172–1181)	
Loss	0.13		0.72 (0.43–2.94)	

^a Combination of process and fuel combustion emissions. ^b EF based on non-peer-reviewed and publicly unavailable literature or expert opinion. ^c EF based on non-peer-reviewed and publicly available literature. ^d EF derived from on non-peer-reviewed and publicly available literature, but it is not clear how EFs were calculated. ^e Actual O&G operator's data. ^f Calculation based on peer-reviewed study and O&G operator's activity data. ^g Calculation based on peer-reviewed study and activity data derived from the NAEI estimate. ^h Calculation based on US EPA EF and activity data derived from the NAEI estimate.

mean regional emission of 2800 kg CH₄ h⁻¹, corresponding to a regional DE of 0.94.⁴⁶ Here we note, the average wind speed during the offshore measurements in Mexico was 6.7 m s⁻¹ and corresponds to a DE of 0.94 using eqn (1).⁴⁶ Both studies suggest the DE is not constant and wind speed should be accounted for, supporting the implementation of eqn (1).

3.1.3. Fugitive emissions. Using an EF of 0.0019 Gg CH₄ Gg⁻¹ NG produced and the 2019 total UK gas production of 40 Tg CH₄,¹⁵ we estimate total offshore fugitive CH₄ emissions at 76 Gg CH₄ (NAEI estimate 7 Gg CH₄ year⁻¹). The least (0.04%) and most (1.41%) emissive facilities observed by Riddick *et al.* (2019) coupled to the measurement uncertainty of ±45% are used as the upper and lower uncertainty bounds and propagate forward to emission bounds of 9 and 831 Gg CH₄ year⁻¹.

3.1.4. Offshore oil transfer. Oil produced on UK FPSOs in 2019 has been estimated at 2.2 million m³¹⁵ and emissions from offshore oil loading have been estimated at 1.1 Gg CH₄ year⁻¹, range 1.0 to 2.4 Gg CH₄ year⁻¹ (NAEI estimate 1 Gg CH₄ year⁻¹). The emission estimate calculated using the US EPA approach (eqn (2)) is within the uncertainty bounds of the NAEI estimate. This validates the approach used by the NAEI, although direct measurements could be used to confirm the emission estimates.

3.1.5. Transfer by pipeline. The most conservative, published measurement of gas loss by pipelines, 0.07%,^{59,60} results in an emission estimate of 25.9 Gg CH₄ year⁻¹ (or 575 kg CH₄ km⁻¹ pipeline year⁻¹) with an uncertainty range of 18.6 to 33.1 Gg CH₄ year⁻¹ (NAEI estimate 3 Gg CH₄ year⁻¹).

3.2. 2019 Revised emission estimates

Table 1 presents CH₄ emission estimates from the NAEI and from this study's improved integrated assessment approach. The NAEI reported total 2019 CH₄ emissions from upstream O&G operations to be 52 Gg with venting being the largest source of emissions (Table 1). Most of the emission estimates



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are derived using a bottom up approach that takes 30 to 40 year-old EFs from available unpublished literature (flaring and loss in pipelines), unavailable unpublished literature (venting and offshore oil unloading) or expert opinion (fugitive emissions). Our improved integrated approach uses the findings from more recent, publicly available research to infer CH₄ emissions from the extraction and transmission processes from the 323 production platforms and 66 FPSOs listed as operational in the UK in 2019.¹⁵ We find emissions to be 289 Gg CH₄ (range: 172 to 1181 Gg CH₄), more than five times larger than the NAEI estimate (Table 1).

Venting is the largest source of offshore emissions. The emission estimate we used for venting (112 Gg CH₄ year⁻¹) taken directly from a UK Government database¹⁵ is and more than twice the NAEI total emission (52 Gg CH₄ year⁻¹), which are derived using an emission factor. Emissions from combustion and processing activities on production platforms are combined to form fugitive emissions of 76 Gg CH₄ year⁻¹ and are based on direct measurement of emissions from offshore platforms in the North Sea.⁴ Offshore oil unloading emissions of 1 Gg CH₄ year⁻¹ were calculated from an algorithm generated by the US EPA and the amount of oil produced by FSPO. Methane emissions from high pressure pipelines are estimated at 26 Gg CH₄ year⁻¹, based on an estimate of 575 kg CH₄ km⁻¹ pipeline year⁻¹, this value seems reasonable as it suggests the pipelines are of medium to high quality, as identified by the IPCC. Overall, the total emission estimate calculated using recent EFs is over five times larger than the NAEI estimate of 52 Gg CH₄.

3.3. Global variability in methane leakage from oil and gas operations

The UK provides annual estimates of the volume of CH₄ flared or vented, a clear government flaring/venting policy, and a governmental regulatory body overseeing emission targets, legislation, regulation and monitoring strategies.^{1,15,64-66} Globally, only Alberta, Canada better regulates CH₄ emissions than the UK, using legislation specifying the quantity of gas that can be flared or vented from onshore production.⁶⁶

The UK was the first major economy to pass a net zero emissions law in 2019 which set a target requiring the UK to bring all greenhouse gas emissions to net zero by 2050.⁶⁷ In 2021 the UK passed another law that requires carbon emissions be reduced by 78% by 2035 compared to 1990 levels.⁶⁸ The UK aims to reduce upstream CH₄ emissions by: (1) minimizing purge flow vent systems; (2) maximizing flash gas recovery; (3) measuring CH₄ emissions using drone sensor surveys and infra-red detection; plus a variety of undefined strategies including: new projects, new techniques, reprioritizing operations (on/offshore), use of digital dashboards, digital machine learning and artificial intelligence technology.⁶⁹

To gain an understanding of how emissions may vary regionally, facilities around the world are presented in Section S4 (ESI[†]) grouped into regions with data collated on regional regulation (Section S4, ESI[†]).⁶⁴⁻⁶⁶ In general, ~40% of platforms must comply with venting, flaring and leak detection and repair (LDAR) regulations (we have assigned these Category 1 status),

Table 2 Comparison of the loss (% of production) and emissions (Em; Gg CH₄ year⁻¹) from an "average" offshore platform producing 400 Gg CH₄ year⁻¹ in each of the 3 regulatory Categories (Cat) as shown in Section S3 (ESI)

Source	Cat 1		Cat 2		Cat 3	
	Loss	Em	Loss	Em	Loss	Em
Venting	0.28	112	0.28	112	9.50	3812
Flaring	0.18	74	0.18	74	0.00	0
Fugitive	0.19	76	0.58	234	0.58	234
Offshore oil	0.00	1	0.00	0	0.00	1
Pipeline	0.06	26	0.06	26	0.06	26
Total	0.72	289	1.11	446	10.32	4141

10% of platforms have flaring regulations but no regulation on venting or LDAR (Category 2 status) and we estimate ~50% of global platforms do not have any regulations controlling their venting, flaring or LDAR practices (Category 3 status).

We suggest Category 1 represents the base-case, similar to regulations in the UK, with CH₄ emissions of 0.97% of NG production (Table 2). Category 2 platforms have venting and flaring rates similar to the UK, but gas from process and combustion activities are likely vented to the atmosphere and result in CH₄ emissions equal to 1.28% of NG production. Category 3 platforms are a worst-case scenario where CH₄ is freely vented to the atmosphere, resulting in the emission of 10.3% of production.

4. Discussion and conclusions

4.1. Reassessment of CH₄ emission for upstream UK oil and gas operations

The 2019 NAEI estimated total emissions from upstream O&G operations (venting, flaring, process emissions, fuel combustion, offshore oil loading, transfer by pipeline and onshore oil/gas terminals) at 52 Gg CH₄. Our integrated approach, which uses direct measurements and top-down studies and published data, estimates 2019 CH₄ emissions at 289 Gg CH₄, five times the current NAEI estimate. This may be a lower bound estimate as (i) venting in the North Sea is reported to have increased from 5 Gg CH₄ year⁻¹ in 2016 to 136 Gg CH₄ year⁻¹ in 2020 (reported as 112 Gg CH₄ year⁻¹ in 2019) despite little change in oil or gas production¹⁵ (ii) although we assume flares operate at optimal efficiency it is likely they are not optimized^{16,48,49} and (iii) we assume that CH₄ combustion slip from compressors, VRUs and condensate tanks are routed to the flare which is unlikely to occur.⁷⁰ Total emissions calculated here are in-line with recent preindustrial carbon-14 estimates that indicate present day fossil CH₄ emissions are underestimated by up to 40%⁷¹ and are consistent with satellite observation of the Permian Basin in the US that suggest US EPA underestimates emissions by a factor of six.⁷²

4.2. Policy Implications

Accurate estimates of GHG emissions are fundamental to accurate projections of climate change in Earth system models and critical in identifying optimal mitigation targets/strategies.¹⁰ The United Kingdom has joined over 100 countries in the Global



Methane Pledge to reduce CH₄ emissions by at least 30% from 2020 levels by 2030¹¹. Reducing emissions from offshore oil rigs will be critical to fulfil this pledge. The difference between current estimates used by NAEI and our estimates, which use more recent research findings, strongly suggests that the current methods of compiling national GHG inventories in the UK, and likely elsewhere, are outdated (oldest EF derived in 1982) and systematically underestimate emissions.^{30,20} Inventories, such as the NAEI, that rely on EFs obtained from industrial studies and unpublished research that has not been independently validated, require improvement especially as they are currently used to inform the IPCC and will be used in evaluating Methane Pledge commitments. The upstream O&G industry operates in challenging conditions and at the limit of where *in situ* measurements can realistically be made. Remote sensing of CH₄ emissions from offshore facilities is in development and quantification methods have not yet been fully validated.^{30,31} Direct measurement of emissions from offshore remote production platforms in a range of weather conditions presents significant challenges but given the relative size of the potential emissions, it is important that these emissions be better constrained and more accurately reported in national inventories in order to receive appropriate attention for mitigation. Emission factors should be improved and activity levels for various processes reported transparently.

We estimate that the UK loses 289 Gg CH₄ year⁻¹ from upstream O&G production. Our results indicate that the NAEI emissions, which are reported and independently verified by the BEIS, are underestimated by a factor of five. Thus, the impact of UK upstream O&G CH₄ emissions on global climate is underestimated and a clear indication of the largest sources and most beneficial mitigation strategies is lacking. Currently, the emission estimates generated by the NAEI are too uncertain to be used in GHG emissions auditing, such as reporting to the IPCC.

Currently, global CH₄ emissions from the O&G sector are estimated at 1.6 Tg CH₄ year⁻¹, based on a 0.32% baseline leakage rate suggested by the OGCI.⁷³ If global emissions from upstream O&G operations are similar to the UK, *i.e.* 0.72% of production, they would be approximately five times higher than currently estimated, *i.e.* 3.6 Tg CH₄ year⁻¹. However, the UK estimate in this study is based on UK venting, flaring and LDAR regulations and may not apply to production platforms globally. Rather than the OGCI estimate of 0.32% of production lost, we suggest global CH₄ emission from the oil and gas sector could lie between 0.72% (Category 1) and 10% (Category 3) of production, depending on where the gas is extracted.

Although the emissions presented in this study are substantially higher than those currently reported, they present high yield opportunities for mitigation as long as baseline emissions are estimated in a clear and transparent way. Given that net CH₄ emissions are a small residual of a large source and sink⁷⁴ and CH₄ has an atmospheric lifetime of ~12 years, reducing overall leakage by a relatively small percentage could result in a significant reduction in atmospheric concentrations,^{75,76} a resulting reduction in radiative forcing from CH₄, a reduction

in the rate of climate warming, and a reduction in the formation of tropospheric ozone which has detrimental effects on human health and vegetation.

4.3. Looking ahead

This study highlights the importance of improving the accuracy of CH₄ emission inventories in the UK and globally. The use of direct measurements to improve CH₄ emission estimates by generating realistic EFs and activity levels is essential. Direct-measurement techniques are under development by the UK Government and the OGCI.⁷⁷ In addition to directly improving emission estimates, additional measurements that improve current EFs and generate EFs for previously overlooked processes are also needed.

Detecting CH₄ leakage from offshore oil and gas platforms would benefit from improved remote sensing of CH₄ over water. Several technologies are making progress with this. The recent development of capturing sun glint reflection from water surrounding the observation target has allowed for offshore CH₄ emission quantification using airborne imaging spectrometers in 2021³¹ and satellites in 2022.⁷⁸ The major shortcoming of these remote sensing technologies is that quantification thresholds are relatively high, 10+ kg CH₄ h⁻¹ for aircraft and 100+ kg CH₄ h⁻¹ for satellites, and the duration of measurement is very short, less than 10 s for satellites. This means that remote sensing could be used for detecting inefficient flares, large leaks on platforms or very large pipeline leaks, but unlikely to currently be able to quantify leaks with varying rates or smaller continuous leaks. Such methods are also unlikely to observe the majority of offshore emissions, *i.e.* typically short-duration venting or offshore oil unloading. Continuous monitors would be better at quantifying these smaller intermittent emissions, but to date only one detection system, the Honeywell Rebellion gas cloud imager, has achieved Intrinsically Safe (IS) status. IS certification is expensive and required for a technology to be permitted on an offshore platform. Given that offshore production is a relatively small market (~1300 offshore platforms worldwide) and many countries do not regulate emissions, the cost of IS status is high. Offshore environments are generally harsh on technology which has meant that offshore continuous monitoring has not been appealing to other system developers. This is likely to remain the case until there is a significant financial incentive for research, development and deployment of sensors suited to the harsh conditions found off-shore.

As countries around the world recognize the importance of reducing CH₄ leakage to slow the rate of climate change and attempt to meet the Global Methane Pledge to reduce CH₄ emissions by at least 30% from 2020 levels by 2030, funding of efforts to improve detection of CH₄ leakage *via* remote sensing should increase. As a participant in the Global Methane Pledge, with most of its leakage occurring off-shore, the UK is a logical contributor to improve technology for off-shore CH₄ leakage, monitoring and reporting. Such efforts would increase the accuracy of its greenhouse gas emission inventory.



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As described in the introduction, one common issue with currently available top-down emission quantification methods is that, even though they work over land, it is unclear how well they will work offshore. Onshore leak detection and quantification methods are routinely tested at controlled release sites, such as Colorado State University's Methane Emission Technology Evaluation Center (METEC). Offshore measurements will remain highly uncertain until the methods are tested against controlled releases from offshore facilities. Given the magnitude of emissions indicated by our research, we suggest that the quantification and mitigation of offshore CH₄ emissions should be a UK priority.

Author contributions

S. N. R. conceived and designed the study, conducted the formal analysis and wrote the original manuscript. D. L. M. acquired funding, validated results, and edited and helped write the final manuscript.

Conflicts of interest

There are no conflicts to declare.

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