The Greenhouse Gas Emissions Profile of Coal Bed Methane (CBM) Production: A Review of Existing Research

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Contents

1. Introduction

1. Methane, the major constituent of natural gas, is present to varying extents in all coal seams, produced during the process of coal formation. It has, historically, been a significant explosion and asphyxiation hazard to mining operations. Ventilation of mine workings and deliberate degasification in advance of mining are undertaken to reduce this hazard. However, methane is also a long lived greenhouse gas (GHG) and coal mining operations are a significant source. Coal production and handling accounts for 5% of current UK methane emissions, down from 18% in 1990 (DECC 2013).

2. Coal seams are in some locations recognised as productive sources of gas for energy, variously termed coal bed methane (CBM) or coal seam gas (CSG).[1] CBM is regarded as an ‘unconventional’ resource, as the methane is held within a low porosity rock formation. Methane molecules are both adsorbed to the surface of the porous coal formations and present in a gaseous state within fissures known as cleats. Wells are drilled into the coal seam vertically, and in some cases also horizontally, and formation water present is pumped out to reduce pressure and allow the flow of gas. Gas is collected on the surface and either directly combusted to generate electricity or processed for injection into the mains gas grid. Because of the low permeability of coal formations, CBM production typically involves more wells than conventional gas fields.

3. This report offers an overview of greenhouse gas emissions profile of coal bed methane production from the existing academic and grey literature[2]. It does not provide any new empirical evidence although additional calculations have been performed to allow for comparison between studies and with data for other sources of natural gas. Having examined the available literature, the report identifies where there are gaps that are relevant to UK development of CBM.

2. Greenhouse Gas Emissions Accounting for Energy Sources

4. The Intergovernmental Panel on Climate Change identifies four long-lived well-mixed greenhouse gases (GHGs) as responsible for the bulk of the anthropogenic radiative forcing that is driving climate change (Solomon et al. 2013). These are carbon dioxide (CO_2), nitrous oxide (N_2O), halocarbons (CFCs and HCFCs) and methane (CH_4). Emissions of these gases accumulate over decades, trapping heat within the Earth’s atmosphere. Other GHGs include sulphur hexafluoride (SF_6), carbon monoxide (CO), nitrogen oxides (NO_x) and the groups of compounds hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and Non-Methane Volatile Organic Compounds (NMVOCs). Fossil fuel production and consumption causes the release of a number of these gases but most significantly carbon dioxide and methane.

5. Different GHGs have different heat trapping properties, lifespans in the atmosphere, and interactions with other atmospheric components. A number of metrics are available for the comparison of the warming effect of different GHGs. Global Warming Potential (GWP) is the most commonly used metric for policy appraisal and Life Cycle Assessment (LCA). It integrates the warming effect of an instantaneous release of gas relative to carbon dioxide as a reference, over a chosen time period, typically 100 years. The use of different time periods and different sources for GWP estimates can be a significant factor affecting the quantitative and qualitative conclusions of comparative emissions accounting studies. This will be discussed further in section 4.

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[1] These terms are used interchangeably, CSG predominating in Australia, CBM elsewhere.

[2] Grey literature is a collective term used to describe technical reports from university research groups, commercial consultancies, think tanks, and government departments and laboratories.

6. Attribution of GHG emissions from industrial, agricultural, commercial or domestic activity can be done from direct measurements of sources, aggregated to a relevant scale such as a nation or industry (so called 'bottom up' accounting) or by dividing field measurements of atmospheric concentration amongst known measures of activity (so called 'top down' accounting).

7. Life Cycle Assessment is a technique that seeks to identify the complete set of environmental impacts of a product or service, throughout its whole life-cycle from raw materials, through manufacturing to use and disposal. A boundary is defined and an inventory of the impacts of interest is created. This is then allocated to each 'functional unit' of the product or service. In the case of energy sources, this is typically either a unit of thermal energy (e.g. joules, J) or electrical energy (e.g. kilowatt hours, kWh) provided by the source upon use. This may or may not include the impact of delivery to an end user, depending upon the boundary chosen and the purpose of the comparison.

8. A 'carbon footprint' is an informal expression for the comparative GHG impact of a product or service, normalised to a comparable functional unit. In the case of fossil fuels, the carbon footprint includes both the direct emissions of GHGs from the combustion of the fuel in use, and the indirect emissions from the activities involved in the extraction, processing and distribution of the fuel. For instance, methane released by a mine in the production of coal could be measured and divided amongst the quantity of coal produced. This could then be added to, *inter alia,* the emissions from oil burned in the coal's transport, and the carbon dioxide released in the coal's combustion.

3. Sources of Greenhouse Gas Emissions in CBM Production

9. This section concerns itself with the 'upstream' GHG emissions from CBM production. In the UK context, natural gas produced from CBM wells will most likely be distributed and combusted in the same way as gas from other sources i.e. predominantly electricity generation, in the same generator units, and for domestic & commercial heating. As a result, comparison of different 'downstream' aspects of the emissions profile is not considered.

10. Emissions may arise directly from gas production due to the combustion of fossil fuels, either for energy (e.g. transport, drilling) or safety (e.g. flaring). There may also be deliberate venting of methane or carbon dioxide for safety, cost or convenience. Fugitive emissions are an unintentional additional direct source, arising from leaks in valves, compressors and the like as well as accidents on site. Pilot wells often have an emissions profile distinct from production wells; in the case of CBM exploration cores typically have low emissions as without dewatering gas flow is low, whilst pilot wells are often not associated with collection and processing infrastructure and so initial gas flows may be vented or flared (Day et al. 2012).

11. The possibility of the creation or enhancement of subsurface movement of methane, carbon dioxide and other gases, through rock fissures, groundwater and sub-soil has also been raised in the academic literature (Tait et al. 2013) but not yet adequately proven or quantified.

12. Indirect emissions include those from the materials and equipment used in the production process, including for instance the manufacture of cement and steel for well construction and the treatment of produced water.

13. Table 1 illustrates the sources of emissions that have been identified across the lifecycle of CBM production (adapted from Skone & Littlefield 2013; Hardisty et al. 2012; Skone et al. 2011).

Table 1 Sources of emissions from CBM Production

Life Cycle Stage	*Activity*	*Example emissions sources*
Raw Material Acquisition		
- Extraction	Well construction	Combustion of diesel for drilling machinery on site and transport to site, including exploration and pilot wells. Cement and steel production for wells. Land clearance.
	Well completion	Episodic emissions from flaring or venting of gas before capture equipment installed at wellhead. Energy for dewatering and hydraulic fracturing (in some cases).
	Workovers	Energy and materials for cleaning of wells. Methane releases during workover.
	Other point source emissions	Well head and gathering equipment.
	Valve fugitive emissions	Leaks from pneumatic valves not accounted for as part of other assemblies.
	Other fugitive emissions	
	Water treatment	Energy for treatment and disposal of produced water.
	Site remediation	
- Processing	Acid gas removal	Energy consumed and GHGs released during amine recovery.
	Dehydration	Combustion and venting emissions from glycol regeneration.
	Other fugitive emissions	
	Other point source emissions	
	Valve fugitive emissions	Leaks from pneumatic valves not accounted for as part of other assemblies.
	Compressors	Energy consumed and GHG leakages from production compressors.
Raw Material Transport	Pipeline construction	Manufacture and installation of steel piping.
	Pipeline compressors	Energy consumed and GHG leakages from pipeline compressors.
	Pipeline fugitive emissions	Minor leakages through joints etc.
End Use	Combustion	CO2 and unburned methane.

14. The environmental report from the Strategic Environmental Assessment For Further Onshore Oil and Gas Licencing, conducted by AMEC for DECC (2013) aggregates coalbed methane into shale gas and oil modelling with limited specific consideration (see section 5.4, p.98). The report uses estimates of numbers of wells and volumes of vented, flared and fugitive methane emissions from shale gas

production scenarios and reports (MacKay & Stone 2013; AEA 2012) without distinguishing CBM. On climate change it finds that "*…for conventional and unconventional oil and gas and VCBM exploration, significant negative effects in respect of greenhouse gas emissions (GHG) at the sectoral level (i.e. as compared to the effects from the existing oil and gas sector) are to be expected during Stage 2 (exploration drilling with coring and hydraulic fracturing) and Stage 3 (production development). However, these effects are unlikely to be significant in terms of emissions at the national level.*" (DECC, 2013, p.117). Similarly, the Environment Agency report into *Monitoring and Control of Methane from Unconventional Gas Operations* notes the potential for CBM development in the UK but does not provide any specific emissions data. Whilst documenting US shale gas emissions factors, it also notes that no detailed data are available for unconventional gas exploration and production where it takes place in the EU (Environment Agency 2012, p.83) although German studies may be available in future.

15. No academic or grey literature reports of the emissions profile of CBM production in the UK were identified whilst scoping this report, given the limited extent of exploration and production activities to date. Internationally, emissions from existing activities ought to be captured within national inventories and reported to the United Nations Framework Convention on Climate Change (www.unfccc.int). However, we have identified just two quantitative life cycle assessments that provide GHG emissions normalised to the energy within the gas produced; one in the academic literature (Hardisty et al. 2012) and one in the grey literature (Skone et al. 2011 reports methodology and total emissions; whilst Skone & Littlefield 2013 reports a quantitative breakdown). The data are presented after an overview of each study's parameters and assumptions.

16. A scoping report by the Australian government research organisation CSIRO (Day et al. 2012) is also useful, gathering and discussing quantitative estimates of fugitive emissions. However, it does not provide new empirical data nor an assessment of emissions arising from other aspects of CBM production.

17. The overall intention of Hardisty et al (2012) is to estimate and compare the GHG emissions from electricity generated by different fossil fuel sources in the Australian context and the emissions associated with LNG export to China. It includes a comparison of the efficiencies of different generator technologies and an estimate of the emissions from LNG liquefaction, transport and regasification which will not be discussed here. The authors note that empirical data are scarce for Australian CBM production and generate a field scale estimate of the emissions profile (500 exploration cores, 300 pilot wells, 6000 production wells) that uses emission factors drawn from Environmental Impact Statement forecasts and two prior reports based on similar data (Institute for Sustainable Futures 2011; WorleyParsons 2011). These raw data were not available for inspection. Hardisty et al's base case calculation uses the IPCC 1995 100 year GWP of 21 for methane and assumes that best practice emissions management such that mandatory flaring of gas is undertaken during pilot well testing and production well workovers, and fugitive emissions are low (0.1% of production) in total. They also generate scenarios which include higher proportions of venting, rather than flaring[3], and scenarios based on higher GWP values for comparison. Although the results are not clearly presented quantitatively, the authors suggest that only high (20%) levels of venting of pilot and production well flare streams during completions and workovers increased emissions from field operations substantially (Hardisty et al. 2012, p.887).

18. Skone et al (2011) and the CBM specific summary Skone & Littlefield (2013) draw on a wider programme of life cycle modelling by the National Energy Technology Laboratory (NETL). Emissions

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[3] This leads to an increase in climate change impact due to the release of methane rather than carbon dioxide.

factors for processes and machinery are predominantly taken from the Environmental Protection Agency (EPA) AP-42 database and inventory (EPA 2011). The calculations use the IPCC 2007 100 year GWP of 25 for methane.

19. Converting to common units[4], both Hardisty et al (2012) and Skone & Littlefield (2013) estimate upstream GHG emissions of CBM to be 28gCO2e/kWh(th). Formal uncertainty estimates or ranges for upstream emissions are not presented by Hardisty et al (2012). Skone & Littlefield (2013) indicate a range of between 26 and 31 gCO2e/kWh(th). Full details are provided in Table A of the appendix, where it can be seen that the respective profiles differ. Hardisty et al (2012) estimate a greater proportion of emissions to be attributable to field operations (89% vs 61%) with very little associated with pipeline operations, which account for 35% of the Skone & Littlefield profile.

20. It must be noted that the results are not absolutely comparable, being based upon different GWP multipliers for methane, 21 and 25 respectively. We cannot be absolutely sure that the activity boundaries and emissions sources are the same in each case either.

21. The complete combustion of methane results in 190gCO2e/kWh(th) (MacKay & Stone 2013) so the additional production emission overhead is in this case approximately 15%.

22. In other studies of unconventional gas emissions footprints, key determining factors have been identified as well productivity, often termed Estimated Ultimate Recovery (EUR) and scale of methane emissions at completion (Jiang et al. 2011; Broderick et al. 2011). The profiles presented by Hardisty et al (2012) and Skone & Littlefield (2013) do not suggest that the same is the case for CBM as ‘episodic’ emissions are not dominant. This is a result of both studies assuming low emissions from well completion, and low to no deliberate venting of methane during production. Diffuse fugitive emissions of methane therefore dominate and scale with the volume of gas produced.

4. Comparison GHG Profile of CBM with Other Natural Gas Sources

23. A recent review of the GHG profile of shale gas also presents a comparison with other sources relevant to UK consumption (MacKay & Stone 2013). Figure 6 from this document is reproduced below:

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[4] All numbers are rounded to 2 significant figures as greater precision does not seem justifiable given uncertainties in data and boundaries.

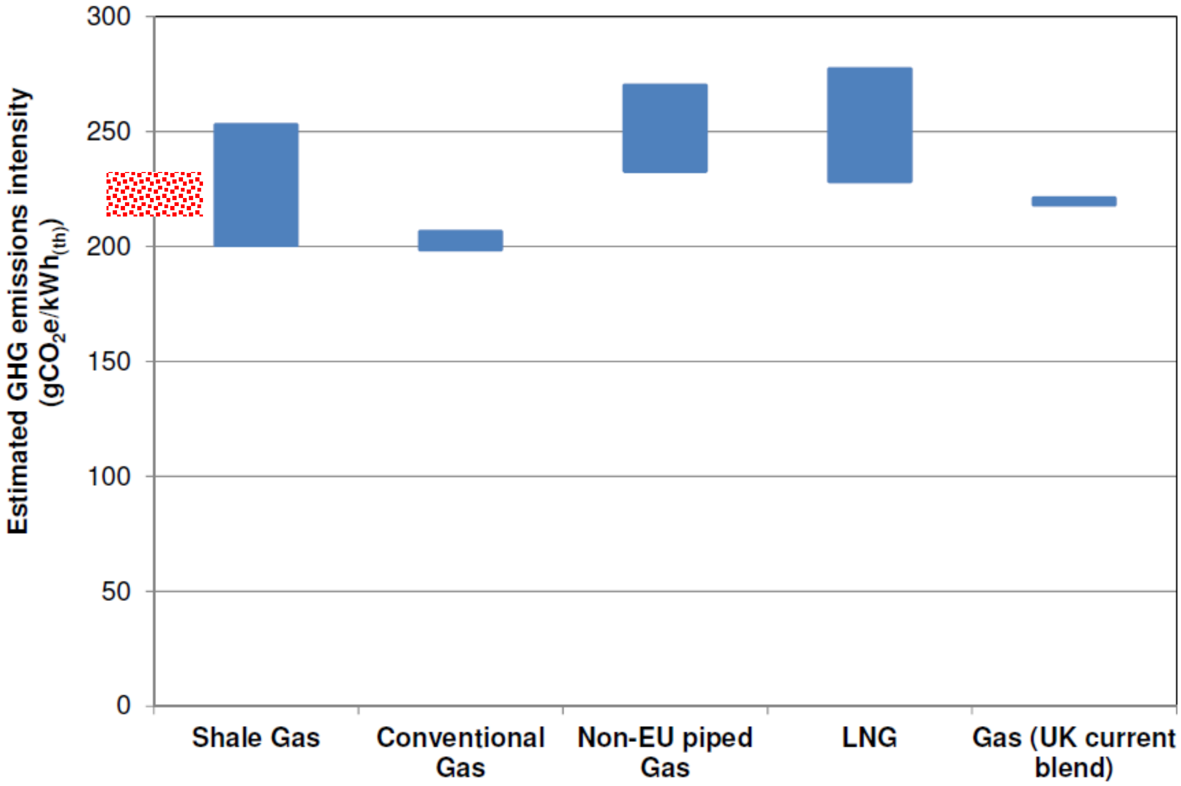

Figure 1 Emissions intensity of UK gas sources (reproduced from MacKay & Stone 2013), red shading indicates approximate range given by Skone & Littlefield (2013)

24. Adding combustion emissions for the gas supplied, 190gCO2e/kWh(th), to the upstream estimates from Hardisty et al (2012) and Skone & Littlefield (2013), results in a total carbon footprint likely to be higher than UK produced conventional gas, within the estimated range for shale gas and at the lower end of non-EU piped gas and LNG. The same caveat of different GWP multipliers must be noted. The discrepancy in pipeline leakage relative to field operations in the CBM studies also persists[5], and similarly we cannot be absolutely sure that the activity boundaries and emissions sources are the same in the CBM cases as those in the MacKay & Stone report.

25. The choice of GWP metric is relevant in these comparative studies. The IPCC Working Group 1 published its Fifth Assessment Report (AR5) in September 2013 and updated the advised values for methane and other GHGs. They advise that methane be considered 28 times more powerful than CO2 on a 100 year basis, if climate-carbon feedbacks are not accounted for, and 34 times if they are. Using these values would tend to increase upstream emissions relative to combustion emissions and increase the importance of mitigation of these sources. In absolute terms this would have the greatest effect on the Hardisty estimate which take methane's GWP as 21 based on IPCC Second Assessment Report (1995). However, in relative terms, compared to coal or renewable sources of energy, such revision is unlikely to make a substantial difference.

26. Choosing a 20 year comparison period can make a much larger difference and alter rankings between fossil fuel sources which have substantially different profiles. For instance coal has a significantly greater carbon footprint that is dominated by CO2 from combustion when compared with gas over a 100 year timescale. This ranking is reversed for higher levels of methane leakage if a

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[5] It is assumed that, within the boundaries of the UK, transport and distribution emissions will be the same for all gas sources regardless of the production method, be it from conventional onshore or offshore reservoirs, hydraulic fracturing of shales, or CBM wells.

20 year comparison is made. The choice of comparison period is a value judgement, not borne from a specific scientific principle but related to the period over which one is concerned about impacts (Solomon et al. 2013, Section 8.7.1.2). Given that equilibrium climate response depends upon cumulative emissions, and is insensitive to the timing or peak rate of emissions, we do not believe this shorter period is appropriate to energy policy (Allen et al. 2009).

5. Research Availability and Data Quality

27. As noted in paragraph 15, little research on GHG emissions from CBM has been identified. The US EPA's (EPA 2010) major report on CBM contains no mention of GHG emissions. Similarly, the World Energy Outlook (2011) "golden age of gas" report fails to discuss emissions associated with CBM, focusing instead on environmental concerns about water (IEA/OECD 2011). World Energy Outlook 2012 does refer to potential emissions from CBD: *"similar concerns [as with tight and shale gas] about emissions attach to coalbed methane production, where significant volumes of methane can be vented into the atmosphere"* (OECD/IEA, 2012, p.38). However, the ensuing discussion focuses on methane in general rather than in relation to coalbed methane.

28. There are also concerns around the general applicability of existing studies, given variation in geology, formation gas composition, and operating practices (Day et al. 2012; Skone et al. 2011), and the effectiveness of mitigation techniques (Allen et al. 2013). Both of the studies cited in section 3 acknowledge limited data quality and uncertainty in their estimates, quantified in the case of (Skone & Littlefield 2013). Day et al. (2012, p.14) note that "…a *comprehensive data set relating to the true scale of fugitive emissions from the CSG industry does not yet exist."*

29. Whilst emissions from energy consumption and raw material manufacturing are relatively straightforward to measure, fugitive emissions are difficult to identify, measure and mitigate by their nature and definition. Given their likely importance in determining the upstream carbon footprint, it would be prudent to monitor UK CBM activities closely. As DECC's Chief Scientific Advisor has recommended for shale gas exploration and production, a thorough research programme is necessary to alleviate these data gaps (MacKay & Stone 2013). This should be done with the appropriate detail, scale and sensitivity to capture both leakage associated with equipment and diffuse releases at the field scale i.e. square kilometre (Environment Agency 2012).

30. Recent US research using a top down methodology at a field scale, i.e. taking total atmospheric measurements and then attributing these to sources, has found discrepancy with bottom up estimates (Pétron et al. 2012). Petron et al's work suggests that mean bottom up estimates of 1.7% leakage of methane are substantially lower than the 2.3% to 7.7% leakage indicated by atmospheric monitoring with dispersion modelling. Such a discrepancy suggests that greater attention should be paid to monitoring and inventories for fossil fuel production in general. Indeed, the GAUGE project (http://www.faam.ac.uk/index.php/current-future-campaigns/485-gauge) will seek to address this at the UK national scale but will not provide site specific data.

31. There may be a number of reasons why substantially more methane is found in the atmosphere than is being accounted for by on site monitoring and emission factor based estimates, both for conventional and unconventional oil and gas production. For instance, measured sites may not be representative of actual practices, or sources of emissions not being recognised, whilst some assumptions may be erroneous, e.g. Skone et al (2011) do not use empirical data for well decommissioning, assuming this incurs 10% of the energy and emissions of the original well construction. They also acknowledge that "*No data are available for the fugitive emissions from around wellheads (between the well casing and the ground)*" and do not account for any post-

production leakage from abandoned wells. Within the report there are also contradictory statements of assumed flaring rate from production wells, 12-18% in Table 2-8 and 51% stated in Table 4-1.

32. Without a specific measurement for the emissions released at completion of a CBM well, Skone et al use the EPA factor for low pressure wells, namely 49.57 Mcf of methane per completion. This stage therefore contributes little to the overall carbon footprint, unlike in the case of shale gas. A number of reports encountered (Day et al. 2012; Hardisty et al. 2012) cite fugitive emissions data from life cycle assessments of US shale gas production, notably from Howarth et al (2011). Although CBM production may also involve hydraulic fracturing it does not in all cases, and low formation pressure reduces the flow of gas on normal completions (Day et al. 2012).

33. Were leakage rates for a coal bed methane field to be found to be in the range measured by Petron et al (2012), methane emissions would contribute approximately 40 to 130 gCO2e/kWh(th) to the carbon footprint (taking the GWP_{100} as 25). This is substantially more than the CBM estimated life cycle range from the literature discussed in Section 4; 26 to 31 gCO2e/kWh(th). However, this field may not be directly comparable with CBM/CSG or a number of reasons (Day et al. 2012) and more representative field measurements from on-going activity, e.g. Australian CSG production, would offer greater insight. For context, added to the combustion emissions of methane of 190gCO2e/kWh(th), the GHG impact of gas produced with this rate of leakage would be 230 to 320 gCO2e/kWh(th). Note that this is not directly comparable with whole life cycle estimates as it does not include other 'midstream' sources of emissions (e.g. transmission, storage & distribution).

6. Conclusion

34. The two studies discussed above (Skone & Littlefield 2013; Hardisty et al. 2012) suggest that the upstream emissions from CBM are a small proportion, in the order of 15%, of the total carbon footprint of the gas including combustion, when venting is restricted and fugitive emissions from production are low. Given data limitations and uncertainty in general applicability we cannot confidently identify a value for potential UK CBM production, however, it is unlikely to be substantially lower than the figures presented as the studies assume careful production methods. Adding combustion emissions for the gas supplied, 190gCO2e/kWh(th), to the upstream estimates from Hardisty et al (2012) and Skone & Littlefield (2013), results in a total carbon footprint likely to be higher than UK produced conventional gas, within the estimated range for shale gas and at the lower end of non-EU piped gas and LNG.

35. If development of CBM proceeds in the UK, it would be prudent to take baseline atmospheric measurements at the site scale before operations commence, such that on site monitoring may reasonably attribute sources of emissions. As DECC's Chief Scientific Advisor has recommended for shale gas exploration and production, a thorough research programme is necessary to alleviate data gaps (MacKay & Stone 2013). This should be done with the appropriate detail, scale and sensitivity to capture both leakage associated with equipment and diffuse releases at the field scale i.e. square kilometre (Environment Agency 2012).

36. If carbon dioxide emissions do indeed dominate the emissions profile of CBM then the greater climate change impact of CBM development would appear to be on the dynamics and economics of the UK and international energy system, as previously noted in relation to shale gas (Broderick et al. 2011; Weber & Clavin 2012; MacKay & Stone 2013).

37. Whatever their quantity, the GHG emissions from CBM operations within the UK ought to be captured and reported in national emissions inventories. If carbon budgets are adhered to, then no

increase in national emissions should arise within the UK. However, this may not be the case for net global emissions as DECC's Chief Scientific Advisor concludes in relation to shale gas production: "*If a country brings any additional fossil fuel reserve into production, then in the absence of strong climate policies, we believe it is likely that this production would increase cumulative emissions in the long run. This increase would work against global efforts on climate change.*" (MacKay & Stone 2013, p.33).

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Appendix A: Breakdown of Emissions Sources

Hardisty et al (2012)	**Data in original unit T CO2e / GJ**	**%**	**Standardised Unit gCO2e/kWh(th)**
Core holes - construction	0.0001	1%	0.36
Pilot Wells - construction and operation	0.0002	3%	0.72
CSG Fields - construction	0.0005	6%	1.8
CSG Fields - operations	0.0069	89%	25
CSG Pipeline - operations	0.00001	0%	0.036
Total	**0.0077**	100%	**28**

Skone & Littlefield (2013)	**gCO2e/MJ**	**%**	**gCO2e/kWh(th)**
Well construction	0.26	3.3%	0.93
Well completion	0.0078	0.1%	0.028
Workovers	0.031	0.4%	0.11
Other fugitive emissions - extraction	0.39	5.0%	1.4
Other point source emissions - extraction	0.023	0.3%	0.084
Valve fugitive emissions - extraction	1.0	12.9%	3.6
Acid gas removal	0.62	7.9%	2.2
Dehydration	-	<0.1	
Other fugitive emissions - processing	0.30	3.9%	1.1
Other point source emissions - processing	0.023	0.3%	0.084
Valve fugitive emissions - processing	-	<0.1	
Compressors - processing	2.36	30.3%	8.5
Pipeline construction	0.016	0.2%	0.056
Compressors - pipeline	0.46	5.9%	1.7
Fugitive emissions - pipeline	2.3	29.5%	8.3
Total	**7.8**	**100**	**28**