Shale Gas: Risk and Benefit to Health

Notes from the literature

Produced by Medact, July 2016

Contents

Introduction

1. In April 2015, Medact published an assessment of the potential health threats associated with shale gas production (SGP), including the process of high volume, hydraulic fracturing ('fracking') and reported that:
   - significant hazards are unavoidably associated with fracking and could impact negatively on the health and wellbeing of local communities;
   - the regulatory framework for fracking in the UK was unclear, incomplete and inadequate, and compromised further by budget and staff cuts to regulatory agencies; and
   - shale gas is not a 'clean' source of energy and may hinder our transition towards a decarbonised energy system.

2. Medact concluded that the risks and threats associated with SGP outweighed its potential benefits, and recommended that it should not be encouraged in the UK.

3. Since publishing that report, Medact has continued to monitor the scientific literature and policy debates concerning SGP. In addition, staff at Medact have been participating in an academic exercise aimed at publishing a systematic review of the scientific research on the health effects of SGP in a peer-reviewed academic journal.

4. *This document* consists of a set of semi-structured notes that have been used to inform a new publication that sets out Medact's position on SGP. This new publication (*Shale Gas Production in England: An Updated Public Health Assessment*) is freely available from the Medact website.

5. The purpose of this document is to provide and enable some access to vast amounts of data, analysis and debate across multiple sectors and disciplines which form the basis for a well-informed, holistic and nuanced understanding of SGP. We hope this document will act as a useful resource for others working on this issue and for interested members of the general public.

6. This document is a work in progress, and will be updated on an ongoing basis. This version (July 6th) will be replaced on July 30th with a more complete and updated version.

7. Having reviewed more of the literature about SGP and having also looked closely at arguments put forward by proponents of shale gas (for example, the 'Task Force on Shale Gas') who argue that SGP can be conducted safely, and that shale gas is a relatively clean, beneficial and strategically-important source of energy, we continue to advise against the development of a shale gas industry in the UK on the grounds that it represents a significant *and* avoidable threat to human health and wellbeing.

Fracking and Unconventional Shale Gas Production

8. The term ‘fracking’ is commonly used to describe a process of shale gas extraction that uses a technique known as ‘high-volume, hydraulic fracturing’ (HVHF) in which high volumes of fluid are injected underground under high pressure. This is designed to fracture gas-bearing shale formations that lie underground, allowing gas to be released and to flow up to the surface where it can be captured for use.

9. The term ‘fracking’ is also commonly associated with the term ‘unconventional natural gas’ (UNG) which is loosely defined to mean gas that is captured using methods that extract gas from unconventional reservoirs such as shale rock.

10. Shale gas is a form of UNG because it is trapped or locked within the fine-grained sedimentary rocks of shale formations that lie underground, and which can only be released once the shale is artificially fractured by HVHF. Although hydraulic fracturing has been used to stimulate oil and gas wells for many decades, the high volumes and high pressures of fluid required to fracture shale rock is a new development.

11. Shale gas production (SGP) is also characterised by new horizontal drilling techniques which allow horizontal boreholes to be drilled for up to 3km at depths of more than 1.5km. These developments in engineering have allowed the oil and gas industry to fracture greater amounts of shale rock that were previously inaccessible or uneconomic.[1]

12. This report is not limited to an assessment of the potential health effects of HVHF, but covers *the entire process* of SGP including the construction of wellpads; the drilling of boreholes; the extraction and use of water; the storage, transportation of waste products; *and* the storage, transportation and ultimate use of natural gas as a source of energy.

Assessing potential harms and benefits

10. An assessment of the potential health impact of SGP has to be balanced and consider both the potential harms and benefits of SGP.

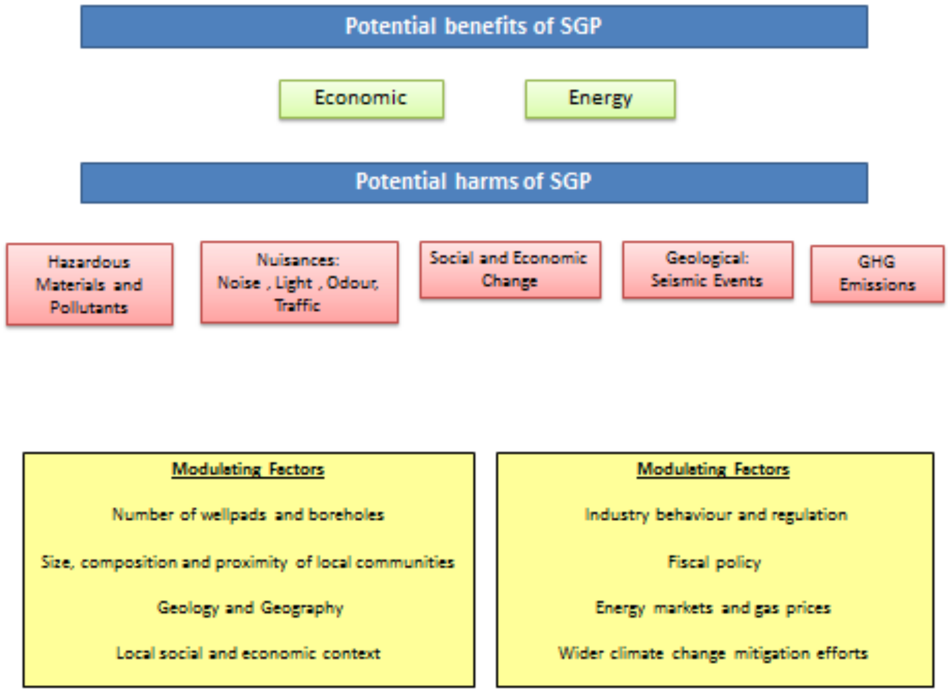
11. We have used a framework (Figure 1) that incorporates two sets of benefits. First, those related to energy itself, which has been a crucial ingredient to the remarkable improvements in human health witnessed over the past 250 years. Second, the potential economic benefits in terms of revenue, job creation and local investment.

12. The framework also describes five sets of potential harms: 1) exposure to hazardous materials and pollutants; 2) exposure to so-called ‘nuisances’ such as noise, light pollution, odour and traffic congestion; 3) social and economic effects that may have an adverse impact on health and

[1] Adgate et al (2014) has noted that the rapid increase in the technology’s development in the US has brought wells and related infrastructure closer to population centres

wellbeing; 4) seismic (earthquake) activity; and 5) the release of greenhouse gases (GHGs) and the effects of global warming and climate change.

Figure 1: A framework describing the potential benefits and harms of SGP



13. The *type* of negative health effects that may arise from these five potential harms are many, and consist of both acute and chronic diseases and illnesses, including those mediated by psychological and emotional pathways. Negative health effects may arise from perceptions of risk which can result in anxiety, stress and fear.[2] Some effects may be experienced immediately, whilst others (such as exposure to carcinogenic toxins) may take many years.

14. The framework above excludes occupational health risks related to accidents or equipment malfunctions on and around the wellpad. There are few data specific to SGP, the oil and gas industry as a whole is known for being relatively dangerous and having a high occupational fatality rate.[3] [4]

15. Blowouts can cause drill pipe, mud, cement, fracking fluids, and flowback to be ejected from the bore and expelled at high pressure. Gas well blowouts can be very dangerous since a spark can set off an explosion. Fires can involve other equipment on the well pad, releasing additional fumes, smoke, and volatiles. Historical data indicate that blowout frequency is approximately 1

[2] Luria, Parkins and Lyons (2009) 'Health Risk Perception and Environmental Problems: Findings from ten case studies in the North West of England'. Liverpool JMU Centre for Public

[3] Adgate JL, Goldstein BD and McKenzie LM, 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. Environ. Sci. Technol 48 (15), pp 8307–8320

[4] Witter, R. Z.; Tenney, L.; Clark, S.; Newman, L. Occupational exposures in the oil and gas extraction industry: state of the science and research recommendations. Am. J. Ind. Med. 2014, in press.

per 10,000 wells.[5] Published data from the Marcellus Shale indicates a blowout risk of 0.17% for the years 2005 – 2013.[6]

16. Because climate change is one of the biggest threats to human health this century, SGP cannot be considered in isolation of the global need to radically and urgently reduce GHG concentrations. However, the potential negative impacts of climate change on health are not limited to populations living in and around SGP sites, but extend across the country and globe.

17. In assessing the potential harms and benefits of SGP, it has to be recognised that any potential future outcomes are dependent on a range of modulating factors that are context-specific (Figure 1).

18. Clearly, the scale and intensity of SGP, and the size, composition and proximity of local communities, will have a considerable bearing on the level of risk and impact on health. Similarly, the nature of local communities and pre-existing economic activities will determine the extent to which the social, cultural and economic disruption caused by SGP will impact negatively on local communities.

19. The specific geological features of the shale formations and their overlying strata, as well as geographic variables such as the local climate and topography, and the nature of the local ecosystem and road network, are also important in determining the type and degree of risk associated with SGP.

20. The adequacy and effectiveness of regulation and the ethical standards and operating practices of shale gas operators (including the adoption of new engineering technologies and safety improvements) are also important in determining levels of safety.

21. The economic benefits of SGP and their distribution across society are dependent on various factors including future gas prices; the tax and subsidy regime applied to the shale gas industry; the employment practices of shale gas operators; and the adequacy and effectiveness of a sanctions regime in the event of accidents, malpractice or negligence.

22. For these reasons, there is no such thing as a standard fracking operation and one cannot derive a generalisable measure of the harms and benefits associated with SGP. While it is important to learn from experiences of SGP in other settings, especially the United States, lessons must be applied carefully to other parts of the world.

23. Differences between the geology, geography, regulatory environment and energy economy of the US and UK mean that the experience of SGP in the US cannot be transposed to the UK context without care.

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[5] http://www.ogp.org.uk/pubs/434-02.pdf
[6] Davies et al, 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. Marine and Petroleum Geology 56 (2014) 239e254

24. Even within the USA, conditions and practices differ from state to state. According to the California Council on Science and Technology, "*hydraulic fracturing practice and geologic conditions in California differ from those in other states, and as such, recent experiences with hydraulic fracturing in other states do not necessarily apply to current hydraulic fracturing in California"*[7]

25. Another general point is that there is a distributional dimension to the effects of SGP. Both the negative and positive effects will be unevenly distributed across populations along geographic, temporal and social dimensions. The balance of benefit and harm will vary within and between local communities directly affected by SGP, as well as across national and global populations. Even the impact of exposure to chemical hazards will vary between individuals within a community due to the uneven distribution of risk factors such as deprivation, poor diet and pre-existing health conditions that influence vulnerability to the effects of potential hazards.

26. The unequal distribution of harms and benefits across society (including between current and future generations), as well as the need to consider the trade-off between harms and benefits, involves ethical considerations and the accommodation of different social values and preferences.

27. The approach taken in this report to assess the health effects of SGP is therefore multi-dimensional and involves a wide range of factors. It stands in contrast to the 2014 Public Health England (PHE) report on shale gas which only addressed the risks associated with chemical and radioactive pollutants, and excluded *"other considerations, such as water sustainability, noise, traffic (apart from vehicle exhaust emissions), odour, visual impact, occupational exposure and wider public health issues, have not been addressed",* as well as the impacts of on climate change.

28. Finally, it needs to be recognised that SGP and the use of HVHF is a new and evolving activity. Research examining the relationship between SGP and health is limited both in terms of the quantity and quality of studies. Although the scientific literature is rapidly expanding, a summation made by Adgate et al (2014) still holds true: *"To date observational studies exploring the association between human health and UNG development have had a number of scientific limitations, including self-selected populations, small sample sizes, relatively short follow-up times and unclear loss to follow-up rates, limited exposure measurements and/or lack of access to relevant exposure data, and lack of consistently collected health data, particularly for non-cancer health effects".*[8]

29. Additionally, because rigorous and independent exposure and health impact studies may be expensive, a tendency to rely on data collected by the industry itself results in bias within the

[7] California Council on Science and Technology, 2015. An Independent Scientific Assessment of Well Stimulation in California: Summary Report. An Examination of Hydraulic Fracturing and Acid Stimulations in the Oil and Gas Industry.
[8] Adgate JL, Goldstein BD and McKenzie LM, 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. Environ. Sci. Technol 48 (15), pp 8307–8320.

existing scientific literature.[9] Incomplete regulation and the application of non-disclosure agreements have also hindered data collection and public interest monitoring and evaluation of the gas industry in the US.[10] [11] [12]

30. Because a degree of judgement is inevitable in the formation of any position on SGP, it is important that conflicts of interest (financial and otherwise) are declared.

31. It is worth noting that there have been a number of controversies associated with research and commentary pieces about shale gas that have been produced by university scientists sponsored by the oil and gas industry.[13] This follows a legacy of the oil and gas industry having actively promoted dubious science aimed at misinforming policy makers and the general public about global warming and its causes.[14] [15]

Hazards, Risks and Harms

Hazardous Materials and Pollutants

32. SGP is an inherently risky activity. According to a United National Environmental Programme (UNEP) briefing note, "hydrologic fracking may result in unavoidable environmental impacts even if unconventional gas is extracted properly, and more so if done inadequately".[16] Furthermore, even if risk can be reduced theoretically, "in practice many accidents from leaky or malfunctioning equipment, as well as from poor practices, regularly occur".

33. Even the industry-funded Task Force on Shale Gas notes that "clearly there is a range of hazards potentially associated with shale gas operations".[17]

34. Among the health risks is exposure to hazardous pollutants, which are typically either airborne or waterborne; and which can affect humans either directly or indirectly.

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[9] Watterson and Dinan, 2015.
[10] Maule A, Makey C, Benson E, Burrows I and Scammel M, 2013. Disclosure of hydraulic fracturing fluid chemical additives: analysis of regulations. *New Solut.* 23(1): 167–87. PM. 23552653.
[11] https://www.guernicamag.com/daily/naveena-sadasivam-in-fracking-fight-a-worry-about-how-best-to-measure-health-threats/
[12] http://www.businessweek.com/news/2013-06-06/drillers-silence-u-dot-s-dot-water-complaints-with-sealed-settlements
[13] Nelson C. Fracking research: playing with fire. Times Higher Education Supplement, https://www.timeshighereducation.co.uk/features/fracking-research-playing-withfire/2007351.article
[14] Miller D and Dinan W. Resisting meaningful action on climate change: think tanks, 'merchants of doubt' and the 'corporate capture' of sustainable development. The Routledge handbook of environment and communication. London: Routledge, 2015.
[15] Jacques PJ, Dunlap RE and Freeman M. The organisation of denial: conservative think tanks and environmental scepticism. Environ Polit 2008; 17: 349–385.
[16] UNEP. Gas fracking: can we safely squeeze the rocks? UNEP Global Environmental Alert Service, http://www.unep.org/pdf/UNEP-GEAS_NOV_2012.pdf (accessed 23 May 2013).
[17] Task Force First report

35. Pollutants, with subsequent risks to both the environment and people, are produced across all stages of SGP including wellpad construction; drilling; hydraulic fracturing; gas extraction, treatment, storage and transportation; the management of waste products; and even after wells have been sealed and abandoned.

36. Among the potentially hazardous chemicals and compounds are: particulate matter (PM); oxides of nitrogen (NOx); volatile organic compounds (VOCs), including formaldehyde, benzene, toluene, ethylbenzene, xylene and poly-aromatic hydrocarbons (PAHs); hydrogen sulphide; ozone; silica; heavy metals such as lead, selenium, chromium and cadmium; and normally-occurring radioactive material (NORM).

37. Elliott[18] systematically reviewed the potential reproductive and developmental toxicity of over 1000 chemicals identified in fracturing fluids and/or wastewater. Data were available for only 24% of these chemicals; 65% of which suggested potential toxicity. Webb et al's 2014 literature review also concluded that chemicals used and produced in unconventional oil and gas operations were known developmental and reproductive toxins.[19]

38. Colborn[20] reviewed the toxicity of 352 chemicals used in US natural gas operations including UNGD and found that 25% were potentially mutagenic or carcinogenic. In addition, over 75% had the potential to cause effects on the skin, eyes, respiratory and gastro-intestinal (GI) systems; 40-50% on the nervous, immune, cardiovascular and renal systems; and 37% on endocrine system. Inevitably, this is not a comprehensive review. Information on the full composition of the products used in the US is limited, partly by commercial confidentiality, and some of the chemicals disclosed have not been subjected to a full toxicological assessment.

39. Stamford et al[21] estimated that human toxicity potential of UK shale gas production for electricity generation to be 3-4 times worse than that of conventional gas, although it was an order of magnitude better than nuclear, solar or coal power.

40. The health risk posed by these different potential hazards varies. Some such as benzene are known carcinogens; some increase the risk of birth defects; while others cause respiratory and cardiovascular disease. The inhalation of benzenes and xylenes can irritate eyes and the respiratory system and cause difficulty in breathing and impaired lung function. Inhalation of xylenes, benzene, and aliphatic hydrocarbons can adversely affect the nervous system with

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[18] Elliott, EG, Ettinger, AS, Leaderer, BP, Bracken, MB, Deziel, NC (2016) A systematic evaluation of chemicals in hydraulic-fracturing fluids and wastewater for reproductive and developmental toxicity, Journal of Exposure Science and Environmental Epidemiology advance online publication, 6 January 2016; doi:10.1038/jes.2015.81.
[19] Webb et al, 2014. Developmental and reproductive effects of chemicals associated with unconventional oil and natural gas operations. Rev Environ Health. 29(4):307-18. doi: 10.1515/reveh-2014-0057.
[20] Colborn T , Kwiatkowski C, Schultz K, Bachran M (2011) Natural Gas Operations from a Public Health Perspective, Human and Ecological Risk Assessment: An International Journal, Vol. 17, Iss. 5
[21] Stamford, L, Azapagic, A (2014) Life cycle environmental impacts of UK shale gas, Applied Energy Vol 134, 1 December 2014, Pages 506–518

effects ranging mild and temporary dizziness, headaches, fatigue, and numbness to serious effects if there is acute and severe poisoning.

41. There is incomplete scientific knowledge about the risk of exposure to many chemical and radioactive hazards. Many of the potential hazards associated with HVHF lack a full toxicity characterization, and there is even less knowledge about the potential risks associated with the 'cocktail' effects of being exposed to multiple hazards simultaneously.[22]

42. Anxiety and fear about exposure can also result in harms to stress, anxiety and other impacts on emotional wellbeing.

Risk of pollution and exposure to hazardous pollutants

43. The risk of pollution depends on many variables including: a) the type and composition of the shale formations; b) the nearby presence of aquifers; c) the number of wells and boreholes; d) the operating practices of fracking companies, including the type of equipment and technology used and the specific constituents of the drilling and hydraulic fracturing fluids; e) the system of regulation in place to ensure safety, including the monitoring and surveillance of pollution; f) leakage rates and the frequency of venting and flaring; and g) the adequacy of facilities for the treatment and management of flowback fluid and other waste materials.

44. Health risks only arise if there is human exposure to pollutants. The magnitude of risk also depends on many variables including: (1) the type of pollutant that humans are exposed to; (2) the amount of pollution and length of time of exposure; (3) the age and health profile of exposed persons; (4) topographical features and meteorological conditions that influence the dispersion of pollutants; and (5) the extent to which households source their drinking water directly from groundwater sources (negligible in the UK).

Water pollution

45. SGP can cause both ground and surface water pollution. The source of pollutants include: a) hydraulic fracturing fluid; b) run off from cuttings and other process residues generated by the drilling of wells; c) 'flowback fluid', including formation and production waters; and d) natural gas itself.

[22] According to the California Council on Science and Technology (2015), a study of a list of chemicals that were disclosed by industry revealed that knowledge of the hazards and risks was incomplete for almost two-thirds of the chemicals. The Council noted that the toxicity and biodegradability of more than half the chemicals used in hydraulic fracturing were un-investigated, unmeasured and unknown. Additionally, basic information about how these chemicals would move through the environment was said to not exist.

46. Water pollution may manifest in different ways: stray gas contamination of aquifers; surface water contamination from spills, leaks, and/or the disposal of inadequately treated wastewater; and the accumulation of toxic and radioactive elements in soil or stream sediments near disposal sites.[23]

47. According to one review, accidents and malfunctions, such as well blowouts, leaking casings, and spills of drilling fluids or wastewater, are more likely to contaminate surface and groundwater supplies than the process of HVHF itself.[24]

48. Another review noted that evidence from the US points to the failure of well cement and casing barriers being the most common cause of water pollution; followed by surface spills (due to leaks, overflowing pits and failures of pit linings) and the accidental release of fracking fluid or flowback.[25]

49. Rahm and Riha's (2014) review reported that spills at the surface were the cause of most incidents of environmental concern including some events with confirmed and significant impacts on local water resources.[26] They also concluded that while good policy and practices can reduce some risks substantially, significant uncertainty remains and that there is a need for more and longer term water quality monitoring.

50. Following concerns about contamination of groundwater in NE Pennsylvania, Reilly et al (2015) analysed samples from 21 drinking water wells suspected of having been contaminated.[27] Samples were taken in 2012 and 2013 and compared against data on groundwater well chemistry from the Pennsylvania Geological Survey and the US Geological Survey reports for 1979–2006. The results revealed evidence of contamination by animal waste, septic effluent or road salt, but no indication of contamination by Marcellus shale flowback.

51. Vidic et al (2013) described the potential for leakages, blowouts and spills to affect water quality and reported only a single case of fracking fluid directly contaminating groundwater, but referred to problems with commercial confidentiality and a lack of baseline data and research.[28]

52. Gross et al (2013) used industry-reported data to assess the potential impact of 77 reported

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[23] Vengosh, Avner et al, 2014. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental science & technology* 48.15: 8334-48.
[24] Adgate JL, Goldstein BD and McKenzie LM, 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. Environ. Sci. Technol 48 (15), pp 8307–8320.
[25] Massachusetts Institute of Technology, 2011. Study on the Future of Natural Gas. MIT Energy Initiative. Available at: http://mitei.mit.edu/system/files/NaturalGas_Report.pdf
[26] Rahm B and Riha S, 2014. Evolving shale gas management: water resource risks, impacts, and lessons learned. Environ. Sci.: Processes Impacts, 2014, 16, 1400
[27] Reilly D, Singer D, Jefferson A, Eckstein Y. 2015. Identification of local groundwater pollution in northeastern Pennsylvania: Marcellus flowback or not? Environ. Earth Sci. 73 (12): 8097–8109
[28] Vidic RD, Brantley SL, Vandenbossche JM, Yoxtheimer D, Abad JD (2013) Impact of shale gas development on regional water quality. Science 340(6134):1235009.

surface spills on groundwater contamination over a year in Weld County, Colorado.[29] Analyses for benzene, toluene, ethylbenzene and xylene showed an exceedance of the Maximum Contaminant Level (MCL) in 90% of cases for benzene, 30% for toluene, 12% for ethylbenzene and 8% for xylene. Given the delay between notification of the spill and the taking of samples, the authors postulate that some levels may have been higher at the time of the incident. The overall number of incidents is small in comparison to the 18,000 active wells, although the self-reported nature of the data indicates a potential for under-reporting.

53. Alawattegama et al (2015) assessed the impact of UNG activity on well water serving a small Pennsylvania community of 190 households by analysing the chemical and microbiological quality of water, community perceptions, and a timeline of operations and failures.[30] Drilling began in late 2007 with a major increase in activity in 2010/11 while the study was conducted from late 2011 to early 2014. 143 households were questioned, 57 samples from 33 wells were analysed for a range of inorganic chemicals, 18 wells were tested for six light hydrocarbons, and bacteria tested for in 26 wells. Of the 143 households who responded to the survey, 35% reported perceived changes in the quality, taste and/or smell of water. Elevated levels of chloride, iron and manganese (with the latter exceeding the MCL in 25 households) were found. Methane was identified in 78% of samples taken, but the levels were low in the majority of analyses. A review of the regulator's data also identified several contraventions including compromised well casings and inadequate plugging that could have caused groundwater contamination. However, the authors acknowledge the challenges in definitively linking the contaminants to UNGD without the availability of pre-drilling baseline data.

54. Heilweil et (2015) sampled and analysed 15 streams in the Marcellus shale play for the presence of hydrocarbons and noble-gas. High concentrations of methane consistent with a non-atmospheric source were found in four of the 15 streams. The isotopic characteristics of dissolved gas in one stream were also suggestive of a local shale source. Modelling indicated a thermogenic methane flux discharging into this stream which was consistent with a reported stray gas migration from a nearby well.[31]

55. Kohl et al (2014) measured strontium in samples of produced waters from six wells in the Marcellus Shale play and a nearby spring over a period four months prior to, and 14 months after, hydraulic fracturing.[32] They found no evidence of migration of produced waters or contamination of groundwater.

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[29] Gross SA, Avens HJ, Banducci AM, Sahmel J, Panko JM, Tvermoes BE. 2013. Analysis of BTEX groundwater concentrations from surface spills associated with hydraulic fracturing operations. RJ Air Waste Manage Assoc 63(4): 424-432, doi: 10.1080/10962247.2012.759166.

[30] Alawattegama SK, Kondratyuk T, Krynock R, Bricker M, Rutter JK, Bain DJ, Stolz JF. 2015. Well water contamination in a rural community in southwestern Pennsylvania near unconventional shale gas extraction. Journal of environmental science and health Part A, Toxic/hazardous substances & environmental engineering 50(5):516-528, doi: 10.1080/10934529.2015.992684.

[31] Victor M. Heilweil, Paul L. Grieve, Scott A. Hynek, Susan L. Brantley, D. Kip Solomon, Dennis W. Risser. Stream Measurements Locate Thermogenic Methane Fluxes in Groundwater Discharge in an Area of Shale-Gas Development. *Environmental Science & Technology*, 2015; 150330072215005 DOI: 10.1021/es503882b

[32] Kohl et al, 2014, Strontium Isotope Test Long Term Zonal Isolation of Injected and Marcellus Formation Water after Hydraulic Fracturing, *Environ Sci Technol* 2014, 48: 9867-9873

56. Drollette et al (2015) examined health and safety contravention reports and sampled private residential groundwater wells in NE Pennsylvania (n=62) and southern New York (n=2) between 2012 and 2014.[33] Fifty-nine samples were analysed for VOCs and gasoline range hydrocarbons, and 41 samples were analysed for diesel range hydrocarbons. Organic and inorganic geochemical fingerprinting, groundwater residence times and dissolved methane concentrations were used to identify potential sources of any contamination. They found trace levels of hydrocarbon contamination in up to a quarter of groundwater samples with significantly higher levels invariably in samples from within 1 km of active UNGD operations. Trace levels of VOCs including BTEX compounds, well below MCLs, were also detected in 10% of samples. Analysis of regulatory data revealed that almost 5,800 contraventions had been reported at 1,729 sites in Pennsylvania between 2007 and June 2014. Geochemical fingerprinting data found no evidence of upward migration and were consistent with contamination from a surface source.

57. Sharma et al (2015) monitored the geochemistry of gas samples from seven vertical Upper Devonian/Lower Mississippian gas wells, two vertical Marcellus Shale gas wells and six horizontal Marcellus Shale wells two months before, during and 14 months after the fracturing of the latter.[34] The results were used to assess gas migration pathways between the hydraulically fractured formation and protected shallow underground sources of drinking water. The analysis indicated that no detectable gas migration had occurred although the authors were cautious, given the limited size of the study, about generalising these findings.

58. Pelak and Sharma (2014) sampled 50 streams in a river basin in West Virginia where there had been past coal mining and current UNGD.[35] Geochemical and isotopic parameters and sampling zones based on the intensity of shale production were used to identify sources of salinity and the effects of the mining and UNGD processes. The study found no evidence of significant contamination from deep formation brines through natural faults/fractures, conventional oil and gas wells, nor any pathways created by shale gas drilling in the region. As the study was a 'one-time snapshot' of water quality, the authors recommended routine monitoring to more effectively assess any impact of shale gas drilling on water quality.

59. Darrah et al (2014) used noble gas and hydrocarbon tracers to distinguish between natural and anthropogenic sources of methane in an analysis of water samples from 113 wells in the Marcellus Shale and 20 wells in the Barnett Shale during 2012/13.[36] Eight clusters of fugitive gas contamination were identified with a chemical signature that suggested the cause to be failures of well integrity

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[33] Drollette BD, Hoelzer K, Warner NR, Darrah TH, et al. 2015. Elevated levels of diesel range organic compounds in groundwater near Marcellus gas operations are derived from surface activities. Proc Natl Acad Sci, doi: 10.1073/pnas.1511474112.

[34] Sharma S et al, 2015. Assessing changes in gas migration pathways at a hydraulic fracturing site: Example from Greene County, Pennsylvania, USA. Applied Geochemistry Volume 60: 51–58

[35] Pelak and Sharma, 2014. Surface water geochemical and isotopic variations in an area of accelerating Marcellus Shale gas development. Environmental Pollution Volume 195: 91–100

[36] Darrah TH, Vengosh A, Jackson RB, Warner NR, Poreda RJ. 2014. **Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales.** PNAS 111(39): 14076-14081, doi: 10.1073/pnas.1322107111.

60. Warner (2013a) sampled 127 drinking water wells and compared them against the composition of flowback samples from Fayetteville Shale gas wells to assess potential contamination by stray gas or fluid migration.[37] Methane was detected in 63% of the drinking-water wells but isotopic characterisation found no spatial relationship with salinity occurrences and proximity to shale-gas drilling sites.

61. Fontenot et al (2013) analysed water samples from 100 private drinking water wells (95 from aquifers in areas of active gas extraction in the Barnett Shale and five reference samples from areas with no wells within 60 km).[38] Levels of several inorganic substances were higher in samples taken within three km of active gas wells compared to those more distant from wells and the reference samples. A number of the elevated results exceeded the EPA Drinking Water MCL including arsenic in 32% of samples. These MCL breaches were randomly distributed within the active gas extraction zone suggesting a variety of contributory factors including changes in the water table, activation of natural sources, and industrial accidents. Twenty-nine private water wells contained detectable amounts of methanol with the highest concentrations in samples from active extraction areas. Comparing the results with historical data prior to gas activities showed significant increases in the mean concentration and maximum detected concentration for arsenic, selenium and strontium.

62. Olmstead et al (2013) assessed the impact of discharged wastewater on surface water in Pennsylvania.[39] This study developed a Geographic Information Systems (GIS) database from several publicly available sources including the results of over 20,000 water quality samples (2000–2011), UNGD locations, consignments of waste to treatment plants, and data on the quality of the receiving water bodies. These data were used to model average impact of UNGD controlling for other factors. Relationships between increasing upstream density of wastewater treatment plants releasing treated waste to surface water and increased downstream chloride concentrations were identified. Relationships between the upstream density of wellpads and increased downstream total suspended solid concentrations were also identified. However, there was no significant relationship between wells and downstream chloride concentrations or between waste treatment and downstream TSS concentrations. The results suggest that upstream shale gas wells do not increase chloride concentrations but the treatment and release of wastewater does, and that increases in TSS associated with UNGD may be due to land clearance for infrastructure development.

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[37] Warner NR, Christie CA, Jackson RB, Vengosh A. 2013. **Impacts of shale gas wastewater disposal on water quality in western Pennsylvania.** Environ Sci Technol 47(20): 11849-11857, doi: 10.1021/es402165b.
[38] Fontenot BE, Hunt LR, Hildebrand ZL, Carlton DD, Oka H, Walton JL, Hopkins D, Osorio A, Bjorndal B, Hu QH, Schug KA. 2013. **An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett Shale formation.** Environ Sci Technol: doi: 10.1021/es4011724.
[39] Olmstead SM, Muehlenbachs LA, Shih J-S, Chu Z, Krupnick AJ. 2013. **Shale gas development impacts on surface water quality in Pennsylvania.** PNAS 110(13): 4962-4967, doi: 10.1073/pnas.1213871110.

63. Warner et al (2013b) examined the impact on surface water quality following discharge of treated Marcellus liquid wastes (including UNGD derived) during 2010-2012.[40] Samples were taken from the treatment plant effluent and downstream and upstream water and sediments. The latter, together with data from other streams, were used as comparators. Samples were analysed for a range of parameters including Cl, Br, Ca, Na, Sr, alkalinity, and NORMs. Levels varied during the sampling period with some concentrations up to 6,700 times higher than the concentrations measured in the upstream river sites. The total radium (Ra) activity in the effluent was well below the industrial discharge limit although sediment levels adjacent to the treatment discharge site were over 200 times greater than background sediment samples. Chloride concentrations around a mile downstream were 2-10 times higher than background. The authors concluded that while treatment reduces the levels of contaminants, wastewater effluent discharge to surface water has a 'discernable impact'.

64. Zhang et al (2015) sampled and analysed wastewater samples from three impoundments in southwestern Pennsylvania in 2010 and 2013 to examine the fate of the most common NORM component Radium-226.[41] Each impoundment contained around five million gallons; two contained untreated wastewater and one held wastewater that had been treated by aeration and sulphate addition. Analysis showed that Ra-226 accumulated in the bottom sludge at levels exceeding the landfill disposal limit and could accordingly be classified as radioactive solid waste.

65. Nelson et al (2015) conducted a small pilot study assessing the levels of natural uranium, lead-210, and polonium-210 in private drinking wells within 2km of a large hydraulic fracturing operation in Colorado before and approximately one year after the start of drilling.[42] Groundwater samples from three residences and single samples from surface water and a municipal water supply were analysed. They found no exceedances of standards and no significant changes in levels before and after drilling. However, the authors recognised the need for further and more extensive monitoring.

66. An industry-supported study by Molofsky et al (2013) assessed the isotopic and molecular characteristics of hydrocarbons in wells in NE Pennsylvania and concluded that the methane concentrations were not necessarily due to migration of Marcellus shale gas through fractures.[43]

67. Li and Carlson (2014) also used isotopic characterisation of produced gas and dissolved methane to examine groundwater wells in the North Colorado Wattenberg Oil and Gasfield and found little relationship. 95% of the methane was of microbial origin and there was no association

[40] Warner NR, Christie CA, Jackson RB, Vengosh A. 2013. **Impacts of shale gas wastewater disposal on water quality in western Pennsylvania.** Environ Sci Technol 47(20): 11849-11857, doi: 10.1021/es402165b.
[41] Zhang et al, 2015. Analysis of radium-226 in high salinity wastewater from unconventional gas extraction by inductively coupled plasma-mass spectrometry. Environ Sci Technol. 2015 Mar 3;49(5):2969-76. doi: 10.1021/es504656q.
[42] Nelson et al, 2015. Monitoring radionuclides in subsurface drinking water sources near unconventional drilling operations: A pilot study Journal of Environmental Radioactivity DOI: 10.1016/j.jenvrad.2015.01.004
[43] Molofsky et al, 2013. Evaluation of Methane Sources in Groundwater in Northeastern Pennsylvania. Ground Water. 2013 May; 51(3): 333–349.

between methane concentrations and the proximity of oil/gas wells. [44]Thermogenic methane was detected in two aquifer wells indicating a potential contamination pathway from the producing formation, but microbial-origin gas was by far the predominant source of dissolved methane.

68. Jackson et al. (2013) found that 82% of 141 drinking well water samples from sites in northeastern Pennsylvania contained methane of thermogenic origin. Levels of methane were strongly correlated with distance to gas wells (average methane concentrations six times higher for homes <1 km from natural gas wells).[45] They suggest that the methane reaches shallow well water through casing failures or imperfections in cement annulus of the gas wells.

69. Hildebrand et al (2015) assessed whether Unconventional Oil and Gas activity had an impact on groundwater quality by measuring the level of natural constituents and contaminants from a 550 groundwater samples overlying the Barnett shale and adjacent areas of north-central Texas.[46] Collectively, these data constitute one of the largest studies of groundwater quality in a shale formation associated with UOG activities. They detected elevated levels of 10 different metals and the presence of 19 different chemical compounds, including benzene, toluene, ethylbenzene, and xylene (BTEX) in a number of samples. They conclude that the findings do not necessarily implicate unconventional UOG extraction as the source of contamination; but demonstrate the need for further monitoring and analysis of groundwater quality.

70. In 2007, a well that had been drilled almost 1200m into a tight sand formation in Bainbridge, Ohio was not properly sealed with cement, allowing gas from a shale layer above the target tight sand formation to travel through the annulus into an underground source of drinking water. The methane eventually built up until an explosion in a resident's basement alerted state officials to the problem.[47]

71. Other studies in the US have also shown a low likelihood of contamination of aquifers where the separation distance from the shale targets is greater than 1000m.[48]

72. Some studies, on the other hand, have shown no association between groundwater pollution and shale gas activities. Siegel et al (2015), for example, analysed groundwater samples from locations near gas wells and found no evidence of systematic increased methane concentration.[49]

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[44] Li H, Carlson KH. 2014. Distribution and origin of groundwater methane in the Wattenberg oil and gas field in northern Colorado. Environ Sci Technol 48(3): 1484-1491, doi: 10.1021/es404668b.
[45] Jackson RB et al, 2013. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction
[46] Hildebrand ZL, et al, 2015. A Comprehensive Analysis of Groundwater Quality in The Barnett Shale Region. Environ. Sci. Technol. 2015, 49, 8254−8262
[47] Ohio Dept of Natural Resources 2008. Report on the investigation of the natural gas invasion of aquifers in Bainbridge Township of Geauga County, Ohio.
[48] Quoting Davies et al, 2012
[49] Siegel et al, 2015. Methane Concentrations in Water Wells Unrelated to Proximity to Existing Oil and Gas Wells in Northeastern Pennsylvania. Environ. Sci. Technol. 2015, 49, 4106−4112.

73. The California Council on Science and Technology (CCST) also found no recorded incidents of groundwater contamination due to stimulation, nor releases of hazardous hydraulic fracturing chemicals to surface waters in California. But the CCST also noted that there have been few attempts to detect such contamination with targeted monitoring, nor studies to determine the extent of compromised wellbore integrity, and that well stimulation chemicals *may* potentially contaminate groundwater through a variety of mechanisms.

74. Siegel el (2015) responded to the Osborn and Jackson results with an analysis of a dataset of 11,300 pre-drilling samples of domestic wellwater in the vicinity of 661 oil and gas wells (92% unconventionally drilled) taken between 2009 and 2011.[50] They found no statistically significant association between methane levels in wellwater and proximity to pre-existing oil or gas wells.

75. Kassotis et al (2013) reported that most water samples from sites with confirmed drilling-related incidents exhibited more oestrogenic, antioestrogenic, and/or antiandrogenic activity than reference samples.[51] Thirty-nine water samples from five sites with a reported spill or incident in the previous six years together with five surface water samples from the Colorado River were taken. Groundwater reference samples were collected from an area with no drilling activity and from two zones with low activity (≤2 wells within 1 mile). Surface water references were taken from two locations with no activity. They found that oestrogen or androgen receptor activity increased from very low in drilling sparse reference water samples, to moderate in samples from the Colorado River, to moderate to high in samples from spill sites. The authors recognised that such effects could be due to sources other than drilling (e.g. agriculture, animal care and wastewater contamination) but considered these to be extremely unlikely. The authors concluded that the results supported an association between gas drilling and endocrine disrupting chemical (EDC) activity in surface and ground waters.

76. Osborn et al (2011), found evidence of methane contamination of drinking water associated with shale gas extraction in north-eastern Pennsylvania. The average and maximum methane concentrations increased with proximity to the nearest gas well and were high enough to be a potential explosion hazard.[52] Chemical analysis confirmed the methane as being thermogenic and coming from the shale extraction sites. The study found no evidence of contamination with deep saline brines or fracturing fluids.

77. Vengosh et al review of published data (through January 2014) found that while direct contamination of water resources by fracturing fluids or the fracturing process was uncertain,

[50] Siegel et al, 2015. Methane Concentrations in Water Wells Unrelated to Proximity to Existing Oil and Gas Wells in Northeastern Pennsylvania. *Environ. Sci. Technol.*, 2015, 49 (7), pp 4106–4112
[51] Kassotis et al, 2013. Estrogen and Androgen Receptor Activities of Hydraulic Fracturing Chemicals and Surface and Ground Water in a Drilling-Dense Region.
[52] Osborn SG, Vengosh A, Warner NR and Jackson RB, 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. PNAS, 8172–8176, doi: 10.1073/pnas.1100682108

there was some evidence for stray gas contamination of shallow aquifers and surface waters in areas of intensive shale gas development, and the accumulation of radium isotopes in some disposal and spill sites. The paper described various interventions that could mitigate these risks including enforcing safe zones (1 km) between shale gas sites and drinking water wells, mandatory baseline monitoring, transparency and data sharing, a zero discharge policy for untreated wastewater, establishing effective remediation technologies for adequate treatment and safe disposal of wastewater, and limiting the use of fresh water resources for shale gas development through substitution or alternative fluids for hydraulic fracturing.

78. A study published in June 2014 by Durham University on the likely radioactivity associated with flowback water concluded that: 'The levels of NORM measured in flowback water are many times higher than found in groundwater, but a long way below the permitted UK exposure limits. Their radioactivity is also lower than that of fluids produced by conventional oil or gas production, or nuclear power. In terms of flux per unit of energy produced, shale gas flowback fluids are also much less radioactive than the burn products of coal-fired power stations. Shale gas exploitation will result in an elevated flux of NORM to the surface, and these flowback fluids must be treated. However, their radioactivity remains low enough that they are unlikely to pose a threat to human health.[53]

Groundwater contamination

79. In the UK where there is good spatial correspondence between potential shale reservoirs and productive aquifers, there has been much concern expressed about the potential for shallow groundwater to be contaminated by hydrocarbons, fracturing fluids and deep formation waters.

80. Understanding the scientific literature on the risks of groundwater contamination is helped by making a few clear distinctions. First, the potential sources of contamination include different processes: a) hydraulic fracturing which takes place more than a thousand metres below the ground; b) drilling and injecting fluid down the well; and c) producing gas (accompanied by production and formation waters) up the well. Second, shallow groundwater may be polluted by both gas (e.g. methane) and liquid (i.e. fracking fluid, and production or formation waters). Finally, the pathway for the pollution of shallow groundwater may include: a) direct pathways from the target formation (via fractures or faults); b) pathways from the well caused by a failure of well integrity; and c) spills and leakages of wastewater from the surface.

81. According to Adgate et al (2014), "the evidence for contamination of groundwater wells with methane, fracturing chemicals, or other process wastes is mixed".[54] Where associations have been found between UNG and drinking water contamination, a lack of baseline data on water quality prior to UNG development have prevented firm conclusions from being drawn.

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[53] The flux of radionuclides in flowback fluid from shale gas exploration, Durham University, Environmental Science & Pollution Research, June 2014

[54] Adgate JL, Goldstein BD and McKenzie LM, 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. Environ. Sci. Technol 48 (15), pp 8307–8320

82. The industry-funded Task Force on Shale Gas also recognises that there is a risk of aquifer contamination and recommends that a risk assessment of aquifer contamination is carried out where appropriate, and that the level of detail of this assessment increases as the separation distance between the frack zone and the aquifer decreases. It also recommends that operators be "required to monitor the size of fractures in UK wells so that over time a more complete statistical picture is built up, to assist the ongoing assessment of aquifer contamination".

83. There is however *some* evidence that shale gas extraction can result in the pollution of shallow groundwater, including sources used to supply drinking water. In particular, there is clear evidence of both fluid and gas having leaked as a result of failure of well integrity *and* of permeable pathways between the well and aquifers then allowing for the contamination of groundwater.

84. Osborn et al (2011) discuss three possible mechanisms for fluid migration into the shallow drinking-water aquifers that could explain the increased methane concentrations: a) upward migration from the target formation; b) leaky gas-well casings, with methane passing laterally and vertically through fracture systems; and c) the process of hydraulic fracturing itself generating new fractures or enlarging existing ones above the target formation, increasing the connectivity of the fracture system and allowing methane to potentially migrate upward through the fracture system.[55] The authors think the first is unlikely, but that the other two pathways are possible. They also note that several models have been developed to explain how gas can be rapidly transport vertically from depth to the surface, including pressure-driven continuous gas-phase flow through dry or water-saturated fractures and density-driven buoyancy of gas microbubbles in aquifers and water-filled fractures, but that more research is needed to determine the mechanism(s) underlying the higher methane concentrations observed.

85. The risk of contaminants *from the fracking zone* directly reaching aquifers is considered by geoscientists to be remote because of the depth at which fracking occurs, the distance between the shale gas production zone and drinking water sources, the presence of impermeable layers of rock between the shale gas production zone and drinking water sources and because fracture

[55] Osborn, Vengosh, Warner and Jackson, 2011. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. PNAS 108 (20): 8172–8176

propagation caused by HVHF rarely extends beyond 600m (and often much less[56]) above well perforations.[57 58 59 60 61]

86. *Even if* a pathway exists, subsurface driving forces are likely to be insufficient to direct the flow of gas and fluids upwards and contaminate aquifers. Flewelling and Sharma (2014) note that having both strong upward gradients and significantly permeable pathways would be necessary to drive upward migration is unlikely.[62] Engelder et al (2014) also describe that various geo-physical forces (e.g. capillary and osmotic forces) are more likely to result in fracturing fluid and formation water being sequestered in the shale formation rather than being transported upward.[63]

87. However, some scientists remain concerned about the possibility of contamination via permeable pathways between the fracking zone and aquifers.[64] Such pathways may be natural (permeable fractures or faults) or artificial (abandoned, degraded, poorly constructed, or failing wells).[65]

88. Smythe (2016) has argued in the online journal Solid Earth Discussions that the presence of natural faults (as opposed to the artificial fractures caused by fracking) and the possibility of upward flow from the target zone made the contamination of groundwater by fracking a greater risk than commonly accepted. He also criticises the joint review of fracking for shale gas by the Royal Society and Royal Academy of Engineering (2012) for not addressing the potential problem of through-penetrating faults in UK shale basins.

89. According to Smythe, modelling studies confirm that fluid from the fracked shale may use faults as an upward migration route to aquifers. The estimated transit times for reaching the near-

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[56] Verdon (in Solid Earth Discussions debate): hydraulic fractures rarely extend more than about 50m above the injection zones, and in the most extreme cases have only propagated a few hundred metres above the injection zone, even where they have intersected pre-existing faults.
[57] AEA Technology, Support to the identification of potential risks for the environment and human health arising from hydrocarbons operations involving hydraulic fracturing in Europe. Report for the European Commission DG Environment 2012.
[58] Davies et al, 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. Marine and Petroleum Geology 56 (2014) 239e254
[59] Vengosh et al, 2014. A Critical Review of the Risks to Water Resources from Unconventional Shale Gas Development and Hydraulic Fracturing in the United States. Environ. Sci. Technol. 2014, 48, 8334−8348
[60] Flewelling S A; Tymchak MP; Warpinski N. Hydraulic fracture height limits and fault interactions in tight oil and gas formations. Geophys. Res. Lett. 2013, 40 (14), 3602−3606.
[61] Warner, N. R.; Jackson, R. B.; Darrah, T. H.; Osborn, S. G.; Down, A.; Zhao, K.; White, A.; Vengosh, A. Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. Proc. Natl. Acad. Sci. U. S. A. 2012, 109 (30), 11961−11966.
[62] Flewelling, S. A.; Sharma, M. Constraints on upward migration of hydraulic fracturing fluid and brine. Ground Water 2013, 52 (1), 9-19.
[63] Engelder et al, 2014. The fate of residual treatment water in gas shale. Journal of Unconventional Oil and Gas Resources 7 (2014) 33–48
[64] See Rozell and Reaven quoting references 44,45, 46,47,48,49 and 50.
[65] Reagan, M. T., G. J. Moridis, N. D. Keen, and J. N. Johnson (2015), Numerical simulation of the environmental impact of hydraulic fracturing of tight/ shale gas reservoirs on near-surface groundwater: Background, base cases, shallow reservoirs, short-term gas, and water transport, Water Resour. Res., 51, doi:10.1002/2014WR016086.

surface vary considerably, ranging from ten to a thousand years in the case of liquid; but in the order of hours to hundreds of days in the case of gas. Smythe quotes literature that he claims helps to substantiate his argument.[66] [67] [68] [69] [70]

90. Smythe also argues that English shale basins are considerably thicker than their US counterparts, and characterised by pervasive and complex faults, some of which extend upwards from the shale to outcrop. According to Smythe, UK shale basins are characterised by having major 'through-penetrating faults' and that the presence of permeable cover rocks in some areas mean that there is an inadequate seal for prevention of upward migration of wastewaters and gas from any future unconventional shale gas site.

91. In contrast, it is extremely rare for faults to extend up to outcrop in US shale basins. As a consequence, while the potential risk of groundwater contamination by the upward migration of fluids via faults is remote in the US, it may be significant in the UK.

92. The views of Smythe have been criticised by many experts on a number of grounds. This includes criticism from authors of papers that Smythe himself has used to support his case, leading to a lively and heated online debate in Solid Earth Discussions.

93. According to Younger, faults are 'hydro-geologically ambiguous' and while some may present permeable zones (most notably where they cut relatively hard rocks such as sandstone, limestone or igneous / metamorphic lithologies); many serve as barriers to flow. Furthermore, even where optimum conditions exist for faults to display permeability, it is rare for this to be continuous over large vertical intervals.

94. Younger goes on to argue that even if one were to believe that faults cutting thick shale sequences (contrary to common experience) are permeable throughout the vertical extent, the risk of actual groundwater contamination is low because a hydraulic gradient that favours the upflow of water (and any pollutants) to shallow aquifers in the context of fracking is unlikely. If anything, the depressurisation of wells to allow gas to enter them during the production phase results in downward gradients over periods of years to decades. Even after the cessation of production (when active depressurisation has been suspended), the re-establishment of an upward gradient is unlikely to result in significant upflow over anything less than geological time. Finally, Younger argues that even if faults are permeable throughout their vertical extent *and*

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[66] Myers T. Potential contaminant pathways from hydraulically fractured shales to aquifers. Ground Water 50, no. 6: 872–882. DOI: 10.1111/j.1745-6584.2012.00933.x, 2012.
[67] Northrup J L. Potential leaks from high pressure hydrofracking of shale, September 8, 2010
[68] Bicalho C C, Batiot-Guilhe C, Seidel J L, Van Exter S, and Jourde H. Geochemical evidence of water source characterization and hydrodynamic responses in a karst aquifer, http://www.sciencedirect.com/science/article/pii/S0022169412003733, 2012
[69] Gassiat, C., Gleeson, T., Lefebvre, R., and McKenzie, J.: Hydraulic fracturing in faulted sedimentary basins: Numerical simulation of potential long term contamination of shallow aquifers, Water Resour. Res., 49(12), 8310-8327, doi:10.1002/2013WR014287, 2013.
[70] Lefebvre, R., Gleeson, T., McKenzie,, J. M., and Gassiat, C.: Reply to comment by Flewelling and Sharma on ''Hydraulic fracturing in faulted sedimentary basins: Numerical simulation of potential contamination of shallow aquifers over long time scales,'' Water Resour. Res. 51, 1877– 1882, doi:10.1002/2014WR016698.

subjected to sustained upward hydraulic gradients, the loading of pollutants would be insufficient to make a detectable difference to the overlying aquifer groundwater.

95. Another counter-argument to Smythe's claims is that complex and pervasive faulting in the UK relative to the US is not substantiated.[71]

96. In his paper, Smythe argues that a case of groundwater contamination in Bradford County, Pennsylvania supports his concern that faults are an important risk factor. He argues that the contamination of drinking water was caused by passage of frack fluid and/or produced water in part through the geology.

97. The case concerns the drilling of five wells in Bradford County in 2009 and 2010 by Chesapeake Energy. Contamination of private water wells with stray gas in the vicinity (1200m away) started almost immediately, and was followed by the Pennsylvania Department of Environmental Protection fining the company $900,000. The company drilled three new water wells to replace three existing wells, but the contamination continued, which included white foam in the water wells, vapour intrusion in the basement of a house, and bubbling of gas in the Susquehanna River. In June 2012 the homeowners won a civil case against the company, which had to buy the properties and compensate the owners.

98. A study (Llewellyn et al) conducted to identify the precise source of the contamination described the most likely cause to have been stray natural gas and drilling or HVHF compounds being driven 1–3 km along *shallow to intermediate depth* fractures to the aquifer.[72] The study authors noted that contamination due to fluids returning upward from *deep* strata would be surprising given that the time required to travel 2km up from the shale would likely be thousands to millions of years, and also because the chemical composition of the drinking waters indicated an absence of salts that would be diagnostic of fluids coming from the shale. The data implicate fluids flowing vertically along gas well boreholes and then through intersecting shallow to intermediate flow paths via bedrock fractures. Such flow is likely when fluids are driven by high annular gas pressure or possibly by high pressures during HVHF injection.

99. Verdon also argues that if fluids have propagated upwards from depth, the migration pathway would be the poorly-cemented wellbore, and that faults and/or fractures only provide a pathway for fluid migration in the upper 300m or so of the subsurface where compressive stresses are low. Verdon also states that had the wells in Bradford County been drilled with the appropriate procedures, no groundwater contamination would have occurred.

100. According to Verdon, while it is possible (even common) that a hydraulic fracture will intersect a fault, if and when it does so, the easiest flow pathway in terms of permeability will be

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[71] Verdon and anonymous reviewer in Solid Earth Discussions.

[72] Llewellyn GT et al, 2015. Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development PNAS | May 19, 2015 | vol. 112 | no. 20 | 6325–6330

along the propped fractures and into the production well. He argues that Smythe misses the fact that the primary permeability pathways created by fracking must be linked to the well bore.

101. Another study which consisted of an experiment where a faulted section of Marcellus Shale was fracked using fluids containing chemical tracers (which allowed the tracking of subsurface fluid movement), found no evidence of upward fluid migration or hydraulic connection from the shale to overlying layers, despite the interaction between hydraulic fractures and faults.[73] This study has been used to discount Smythe's claims, although Smythe argues that the study did not examine a geological situation with 'through-penetrating faults' and therefore has no direct relevance to his argument.

102. A further point of debate raised by Smythe concerns the need to identify faults before and during drilling. According to Smythe, identification of faults within a thick shale sequence such as the Bowland-Hodder Unit is difficult, and that identifying faults intersecting the fracking zone cannot be guaranteed. Smythe argues that before any fracking takes place, faults should be thoroughly mapped and a 'setback' distance be established between the frack zone and the nearest faults.

103. The issue of faults in the UK is underlined by the experience of the only shale well to have been fracked in the UK: Preese Hall in Lancashire which was fracked in 2011 by Cuadrilla to test the shale and which triggered earthquakes. According to Smythe, analyses of two independent datasets – a 3D seismic survey and wellbore deformation – demonstrate that the fault on which the earthquakes were triggered, was transected by the wellbore. Furthermore, he points out that these data contradict the initial conclusion of the operator which claimed that the triggered fault lay hundreds of metres away from the wellbore.

104. Smythe also describes how in 2014 in the Weald Basin in Sussex (Balcombe-2), Cuadrilla drilled a horizontal well along a 40m thick limestone sandwiched between two oil-prone shale layers, the Kimmeridge Clay, and intersected two normal faults neither of which were foreseen by the operator.

105. Westaway, one of Smythe's strongest critics, states that Smythe conflates reporting on what happened at Preese Hall with what will be permitted in the UK in future and that all 'stakeholders' accept the need to do things differently in future.[74] However, he agrees that the actions of Cuadrilla at Preese Hall were far from ideal,[75] and that there have been problems

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[73] Hammack R, Harbert W, Sharma S et al, 2014. *An Evaluation of Fracture Growth and Gas/Fluid Migration as Horizontal Marcellus Shale Gas Wells are Hydraulically Fractured in Greene County, Pennsylvania*; NETL-TRS-3-2014; EPActTechnical Report Series; U.S. Department of Energy, National Energy Technology Laboratory.

[74] Westaway 2016a. Interactive comment on: "Hydraulic fracturing in thick shale basins: problems in identifying faults in the Bowland and Weald Basins, UK" by D. K. Smythe. Solid Earth Discussions, se-2015-134, SC2

[75] For example, Westaway states that the induced seismicity should have been detected earlier (by applying a series of standard tests) so that fracking could have been stopped rather than continuing for almost two months until being 'voluntarily' terminated just before the UK government imposed a moratorium. In addition,

concerning the release of data and information about the incident. According to Westaway, 'something is clearly fundamentally wrong with the present arrangements for implementing the UK government's publically stated commitment to open disclosure and discussion of data pertaining to shale gas development'.

106. Smythe argues that it is unacceptable that current UK regulations permit the drilling of faults (if they are identified) either vertically or horizontally because cement bonding of the casing, either in the deviation zone or in the horizontal section of the well, would be difficult to achieve.[76] As shown at Preese Hall, a well that penetrates a fault can be deformed by seismic activity triggered by HVHF and increase the chance of the integrity of the well bore being degraded.

107. Haszeldine notes that Smythe's Solid Earth Discussion article is likely to be unpopular amongst sections of the UK geoscience community because it goes against the majority academic view that HVHF can be made secure by tightly controlled monitoring.

108. He agrees that the potential for faults to act as leakage conduits for gas or frack fluids are more likely to occur in intensely faulted basins and that geoscientific investigations may have failed to recognise these potential hazards ahead of drilling and after fracking. He states that there are legitimate questions to be asked about subsurface evaluation competence and the ability to recognise faults before or after drilling; the adequacy of current legacy information to position fracking boreholes; and the state of knowledge of fluid and gas flow along faults penetrating towards the land surface.

109. Haszeldine does not think that Smythe makes a compelling case for deep waters being brought up to the surface along steeply dipping faults, but agrees that this hypothesis is worthy of greater investigation, especially as the consequences may be serious or even terminal for drinking water supplies.

110. However, according to Haszeldine, the simple critiques by some commentators that "faults are impermeable" don't stand up to clear evidence of deep *gas migration* to the surface. While the upward migration of fluids from the fracking zone to aquifers is unlikely, gas ascent through pathways along or parallel to fault planes is possible. In short, faults could act as conduits for fugitive gas emissions from fracked basins. Haszeldine also concludes that faults (and fractures) may act as a conduit for both fluids and gas to aquifers at higher subsurface levels from the wellbore in the case of concurrent well integrity failure.

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the in-situ stress dataset collected *during* drilling should have been analysed before the fracking began, rather than afterwards, as this would have shown that faults in the vicinity were already stressed and that fracking might induce seismicity.

[76] The eccentricity of the drill casing with respect to the borehole means that it is hard to flush out drilling mud, and a subsequent cement job may then fail because the resulting cement-mud slurry does not make not a sound bond.

111. Finally, Haszeldine agrees that the regulatory oversight of drilling applications and industrial activity appears to be inadequate and that some of information and insights contained in Smythe's case studies are "remarkable and even shocking as examples of how current practice has not produced anything like technically adequate assurance of high quality for UK citizens". In his view, "the observations made, of pressure leakage at Preese Hall, and of basic subsurface ignorance and technically bad seismic processing at Fernhurst and Wisborough Green are shocking, and could be investigated for mandatory cleanup".

Well integrity

112. As noted above, pollution can occur through leaky wells, during drilling and casing, and even after wells have been sealed and abandoned.[77] [78] The loss of well integrity can potentially lead to direct emissions of gas to the atmosphere and/or subsurface migration of gas and/or liquid to groundwater, surface waters or the atmosphere.[79] [80] Under certain conditions, leaks that continue undetected or are inadequately remedied may also lead to the accumulation of explosive gases.

113. Drillers use steel casing (pipes), cement between nested casings and between the outside casing and rock wall, as well as mechanical devices to keep fluids and gas inside the well.

114. The causes of loss of well integrity include failure of the cement or casing surrounding the wellbore and an improperly sealed annulus. Cement barriers may fail at any time over the life of a well for various reasons including inappropriate cement density, inadequately cleaned bore holes, premature gelation of the cement, excessive fluid loss in the cement, high permeability in the cement slurry, cement shrinkage, radial cracking due to pressure fluctuations in the casings, poor interfacial bonding, and normal deterioration with age.[81] Casing may fail due to failed casing joints, casing collapse and corrosion.[82]

115. The risk of loss of well integrity increases with age as steel corrodes, and as cement shrinks, cracks or disbonds from the casing and rock. Factors that increase the risk of loss of well integrity include: unconventional and horizontal wells; wells being longer and curving laterally; wells

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[77] Kissinger A, Helmig R, Ebigbo A, Class H, et al. Hydraulic fracturing in unconventional gas reservoirs: risks in the geological system, part 2. Environ. Earth Sci. 2013, 70, 3855–3873

[78] Vengosh, Avner et al, 2014. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental science & technology* 48.15: 8334-48.

[79] Ingraffea et al 2014. Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. PNAS 111(30): 10955–10960

[80] Stuart ME, 2011. Potential groundwater impact from exploitation of shale gas in the UK. *British Geological Survey Open Report*, OR/12/001.

[81] Bonnett A, Pafitis D (1996) Getting to the root of gas migration. Oilfield Review 8(1): 36–49.

[82] Ingraffea et al 2014. Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. PNAS 111(30): 10955–10960

being exposed to more intense hydraulic pressures and larger water volumes; the adoption of poor practices by companies (wells being drilled during boom periods in the US have led to operators cutting corners in an attempt to maximise the number of wells drilled).[83] [84] Drilling through strata with pervasive and complex faults also increases the risk of well damage and integrity failure.

116. The structural integrity failure rate of oil and gas well barriers is a subject of debate.

117. According to Davies et al, data from around the world indicate that more than four million onshore hydrocarbon wells have been drilled globally. In their assessment of all reliable datasets on well barrier and integrity failure (including production, injection, idle and abandoned wells, as well as both onshore and offshore wells, exploiting both conventional and unconventional reservoirs), they found datasets that varied considerably in terms of the number of wells examined, their age and their designs. They found that the percentage of wells with some form of well barrier or integrity failure was highly variable, ranging from 1.9% to 75%.[85]

118. In the US, because of the lack of publicly available structural integrity monitoring records for onshore wells *from industry*, studies have relied on data from state well inspection records to estimate the proportion of unconventional wells that develop cement and/or casing structural integrity issues.

119. Davies' own assessment of unconventional wells in Pennsylvania indicated that 6.26% had well barrier or integrity failure, and 1.27% leaked to the surface.

120. Ingraffea et al's analysis of 75,505 compliance reports for 41,381 conventional and unconventional oil and gas (O&G) wells in Pennsylvania drilled from January 2000 and December 2012 found a sixfold higher incidence of cement and/or casing issues for shale gas wells relative to conventional wells.[86] Overall, between 0.7% and 9.1% of the O&G wells developed since 2000 showed a loss of well integrity. The well-barrier or integrity failure rate for unconventional wells was 6.2%. The most common causes were "defective, insufficient or improperly installed" cement or casing and for pressure build-up, apparent as surface bubbling or sustained casing pressure.

121. The same study also identified temporal and geographic differences in risk. Temporal differences may reflect more thorough inspections and greater emphasis on finding well leaks, more detailed note taking in the available inspection reports, or real changes in rates of structural integrity loss due to rushed development or other unknown factors. The predicted

[83] Davies et al, 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. Marine and Petroleum Geology 56 (2014) 239e254

[84] Jackson 2014. The integrity of oil and gas wells. PNAS 111(30): 10902–10903

[85] Davies RJ, Almond S, Ward RS, Jackson RB et al, 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. Marine and Petroleum Geology 56 (2014) 239e254

[86] Ingraffea AR, Wells MT, Santoro RL, Shonkoff SBC, 2014. Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. Proc Natl Acad Sci USA 111:10955–10960.

cumulative risk for all wells in the NE region of Pennsylvania was 8.5-fold greater than wells drilled in the rest of the state.

122. In Considine et al's analysis of records from the Pennsylvania Department of Environmental Protection from 2008 to 2011, between 1% and 2% of wells had one or more potential structural integrity issues reported during that time period.[87] Another study using data from 2008 to 2013 found that 3.4% of all monitored unconventional wells drilled in Pennsylvania might have structural integrity failures related to cement/casing integrity.[88] However, both these studies are limited by the inadequacy of the frequency and completeness of state inspections as a basis for accounting for all incidences of cement/casing failure.

123. Few data exist in the public domain for the failure rates of onshore wells in Europe. It is also unclear which of the available datasets would provide the most appropriate analogues for well barrier and integrity failure rates at shale gas production sites in the UK and Europe.[89]

124. In the UK, the integrity failure rates of onshore (conventional) oil and gas wells are largely unknown. Davies et al (2011) note a small number of reported pollution incidents associated with the few existing active onshore (conventional) wells and none with inactive abandoned wells. They state that this could indicate that pollution is not a common event, but warn that monitoring of abandoned wells does not take place in the UK and that less visible pollutants such as methane are unlikely to be reported. Thus "well integrity failure may be more widespread than the presently limited data show".

125. They call for more research (e.g. a survey of the soils above abandoned well sites to establishing whether there is a loss of integrity and fluid / gas migration following well abandonment), a mechanism for funding repairs on orphaned wells, and an ownership or liability survey of existing wells.

Wastewater management

126. As noted earlier, one of the hazards associated with SGP is the volume and level of toxicity of fluid that is brought to the surface.

[87] Considine T, Watson R, Considine N, Martin J (2012) Environmental Impacts During Marcellus Shale Gas Drilling: Causes, Impacts, and Remedies. Report 2012-1 Shale Resources and Society Institute (State University of New York, Buffalo, NY)

[88] Vidic RD, Brantley SL, Vandenbossche JM, Yoxtheimer D, Abad JD (2013) Impact of shale gas development on regional water quality. Science 340(6134):1235009.

[89] Davies et al, 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation

127. Options for managing large volumes[90] of hazardous flowback fluid and wastewater on the surface include the reuse of flowback fluid for further hydraulic fracturing; on-site or off-site wastewater treatment followed by discharge; and deep well injection.

128. Initially flowback fluid returns to the surface in large volumes and closely reflects the composition of fracking fluid. Later, when the well is producing gas, formation and produced waters are returned in lower volumes, but with higher concentrations of heavy metals, NORM and other contaminants from the shale. This may continue for months after HVHF. In this report, both the initial flowback fluid and the subsequent produced or formation water are considered together as wastewater.

129. High levels of contamination and pollutants in wastewater, and particularly radioactive NORM, require specialised treatment facilities before they can be safely disposed. The actual composition of wastewater fluid is an important factor. Treatment of wastewater with high levels of contamination can be difficult. Removing dissolved salts, in particular, normally requires distillation (which is generally expensive because of the high energy inputs), or reverse osmosis.

130. In the US, the management of wastewater includes storage in open pits; deep well injection (reinjecting wastewater into the ground); transportation to treatment facilities followed by disposal; and on-site treatment with some re-use of water and disposal of remaining liquids and solids. Although some well operators recycle and reuse flowback fluid for hydraulic fracturing, many operators do not due to the cost of separation and filtration.[91] Deep well injection, which is common in the US, is not an option in the UK. Neither is storage in open pits.

131. Difficulties with wastewater treatment that have been reported in the US include the lack of treatment plant capacity or technology[92] and the difficulty in predicting the content and composition of fluid that is brought up to the surface.[93] Some US municipal wastewater treatment facilities have struggled to handle wastewater containing high concentrations of salts or radioactivity.[94] The pollution of some rivers has also been associated with municipal wastewater treatment facilities not being able to handle wastewater with high concentrations of salts or radioactivity.[95]

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[90] The Institution of Civil Engineers estimate that a single well could produce between 7,500 to 18,750 m3 of flowback annually. See written submission to Environmental Audit Committee: Environmental Risks of Fracking Enquiry (FRA070), para 2.1.

[91] Rozell DJ and Reaven SJ (2012). Water pollution risk associated with natural gas extraction from the Marcellus Shale. *Risk Anal* **32**(8): 1382–93.

[92] J.M. Wilson, J.M. VanBriesen, 2012. Oil and gas produced water management and surface drinking water sources in Pennsylvania Environ. Pract., 14 (2012), pp. 288–300

[93] E. Barbot, N.S. Vidic, K.B. Gregory, R.D. Vidic, 2013. Spatial and temporal correlation of water quality parameters of produced waters from Devonian-age shale following hydraulic fracturing. Environ. Sci. Technol., 47 (2013), pp. 2562–2569

[94] See Rozell and Reaven refs 42 and 56

[95] Pennsylvania DEP investigates elevated TDS in Monongahela River. Water and Wastes Digest. October 27, 2008. Available at: http://www.wwdmag.com/Pennsylvania- DEP-Investigates-Elevated-TDS-in-Monongahela-RivernewsPiece16950,

132. In the UK, issues about wastewater management became apparent during the Public Inquiry into Cuadrilla's appeal against Lancashire's decision to reject planning applications for two exploratory shale gas wells (in Roseacre Wood and Preston New Road).[96]

133. One of the issues was the limited capacity and availability of treatment facilities in the UK. Constraints on treatment capacity became more stringent when a change in law required the wastewater to be considered a low level radioactive substance which prohibits ordinary sewage treatment works from being a viable option.

134. The lack of treatment facilities in the UK able to manage NORM-contaminated wastewater is already recognised. In Watson's evidence to the Lancashire Public Inquiry, he notes that the Government is unable to confirm the existence of adequate treatment capacity in the event of shale production at scale and that a likely increase in NORM generation from iron, steel and titanium dioxide production, as well as the decommissioning of offshore oil and gas infrastructure from the North Sea and the anticipated growth in provision of O&G decommissioning services to other countries, are likely to place even more pressure on limited capacity.

135. The problem of limited treatment capacity is illustrated by the considerable volume of wastewater expected from the two exploratory fracking sites that Cuadrilla sought to develop in Lancashire: a DECC Strategic Environmental Assessment reported that a 'high activity scenario' would result in an annual production of 108 million m^3 of wastewater from just two sites which would represent approximately 3% of UK total annual wastewater.[97]

136. Another issue is the transportation of wastewater to treatment facilities. According to Watson, Cuadrilla's estimate of the volume of fluid needing treatment from two exploratory sites in Lancashire would involve transporting a total of 50 million litres, an amount that equates to 1,440 tankers with a capacity of 35,000 litres (360 tanker loads per well). In ordr to transport this volume of fluid to a treatment facility, a potential total tanker mileage of 470,000 miles (approximately 19 times around the earth) would be required, and result in emissions of around 2,000 tonnes of carbon dioxide.[98]

137. According to DECC, on-site treatment and re-use of flowback '*could reduce the volumes of wastewater generated and lessen any effects on offsite treatment infrastructure capacity".*

[96] Cuadrilla's applications include provisions for an extended flow testing period of 18-24 months after an initial 90 day flow testing. It was anticipated that produced fluids would be generated throughout that extended period.

[97] According to Watson, the impact of such a sudden and significant surge in demand, even if only for a relatively short-term, in terms of the opportunity costs to other major users and the consequences of any accidents or disruption at the treatment sites was not considered in Cuadrilla's planning applications.

[98] These figures are conservative, and based on the assumption that the flowback rate would only be 19% of the total water injection during the initial flow testing/exploration period (although confusingly, a figure of 40% was reported elsewhere). The flowback rate over the three months testing at Preese Hall was 70%.

However, this would require more sophisticated equipment. There is also significant uncertainty as to the quantity of flowback fluid which may be suitable for re-use.

Air pollution

138. Air pollutants include: (1) unintended or irregular (fugitive) emissions of gas from the ground, well and associated infrastructure (e.g. pumps, flanges, valves, pipe connectors, and collection and processing facilities); (2) diesel fumes from engines used to power equipment, trucks and generators; (3) emissions from drilling muds[99], fracturing fluids[100] and flowback water; (4) silica dust (silica is used to prop open the shale fractures); (5) venting or the deliberate release of gas into the atmosphere (when there is a safety risk); and (6) the flaring of gas (limited in the UK to exploratory fracking due to the expected requirement for green or reduced emissions 'completions' during the production phase).

139. Moore et al (2014) conducted a critical review of the air impacts of all five stages of the natural gas life cycle (pre-production; production; transmission, storage, and distribution; end use; and well production end-of-life).[101] They identified clear potential for exposure to hazardous air pollutants including particulate matter from diesel powered equipment and truck traffic, VOCs , respirable silica, H_2S, NOx and SO_2.

140. The multiple variables involved in determining the level of air pollution explains why air quality studies carried out in US regions with high levels of unconventional O&G production have yielded variable and conflicting results. For example, Colborn et al (2013) gathered weekly, 2 4-hour samples 0.7 miles from a well pad in Garfield County, and noted a "great deal of variability across sampling dates in the numbers and concentrations of chemicals detected".[102]

141. Air pollution may also arise from the sub-surface. According to Macey et al, "we do not understand the extent of drilling-related air emissions as pockets of methane, propane, and other constituents in the subsurface are disturbed and released to the atmosphere".[103]

[99] During the drilling stage a water-based fluid known as "drilling mud" is circulated through the borehole to lubricate and cool the drill bit and to loosen and collect fragments of rock caused by the drilling ('cuttings').
[100] Fracking fluid may include biocides to prevent bacterial growth; surfactants to reduce surface tension to aid fluid recovery; gels and polymers to increase viscosity and reduce friction; acids; and chemicals to inhibit corrosion of metal pipes. The exact composition will vary from operator to operator, and from site to site depending on factors such as the depth of the operation, the length of the well and the nature of the shale.
[101] Moore C et al, 2014. Air Impacts of Increased Natural Gas Acquisition, Processing, and Use: A Critical Review Environ. Sci. Technol. 2014, 48, 8349−8359
[102] Colborn T, Schultz K, Herrick L, Kwiatkowski C. An exploratory study of air quality near natural gas operations. Hum Ecol Risk Assess 2013. http://dx.doi.org/10.1080/10807039.2012.749447
[103] Macey et al, 2014. Air concentrations of volatile compounds near oil and gas production: a community-based exploratory study. Environmental Health 2014, 13:82 doi:10.1186/1476-069X-13-82

142. According to Goodman et al (2016), small percentile increases in emissions of CO2, NOx and PM were estimated in one prospective study in Haynesville US, for the period from start of construction to pad completion (potentially several months or years), however excess emissions of traffic related NOx on individual days of peak activity can reach 30% over baseline.[104]

143. UNGD's photochemical oxidant formation[105] potential has been estimated to be about nine times higher for UK shale gas compared to North Sea gas when used for electricity generation and 60% worse than coal power (Stamford et al 2014).

144. Goetz et al (2015) used a mobile laboratory to assess air samples from specifically targeted sites associated with shale gas extraction in 2012 in NE and SW Pennsylvania, including over 50 compressor stations and 4200 wells.[106] The samples found no elevation of sub-micrometer particles nor of light aromatic compounds such as benzene and toluene. Methane emissions were detected in the atmosphere and found to be relatively high compared to levels reported elsewhere (e.g. Allen 2013). Of note was large differences in methane emissions believed to be due to differences in operating practices, production volume decline, location of leaks, scheduled versus unscheduled monitoring, and the number and representativeness of sites sampled (to be expected because the Marcellus play does not contain significant oil deposits).

145. Swarthout et al (2015) analysed air samples from across a region surrounding Pittsburgh and compared data from two sites: one with nearly 300 unconventional natural gas (UNG) wells within 10 km and the other a remote location with a single well within 10 km.[107] They found elevated mixing ratios of methane and C2−C8 alkanes areas with the highest density of UNG wells. Source apportionment methods indicated that UNG emissions were responsible for the majority of mixing ratios of C2−C8 alkanes, but accounted for a small proportion of alkene and aromatic compounds. The VOC emissions from UNG operations were also associated with levels of ozone formation that compromised federal air quality standards. The findings suggest that while local people were exposed to levels of HAPs around four times higher than populations remote from gas operations, the concentrations of VOCs were well below hazardous levels. This was reflected in the low HI for both cancer and non-cancer risk calculated with a modified version of the method used by McKenzie (2012).

146. Vinciguerra T et al (2015) used ambient levels of ethane, a marker for fugitive natural gas emissions, and reported that daytime ethane concentrations had increased from about 7% of total measured non-methane organic carbon to about 15% from 2010 to 2013 in areas overlying the Marcellus Shale.[108] This trend was not observed in a control area with similar urban sources

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[104] Goodman et al, 2016 Investigating the traffic-related environmental impacts of hydraulic-fracturing (fracking) operations, Environment International 89–90 (2016) 248–260

[105] Photochemical oxidant formation (production of ground-level ozone) is due to reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOC) induced by sunlight

[106] Goetz J, Floerchinger C, Fortner E et al, 2015..Atmospheric emission characterization of Marcellus Shale Natural Gas Development Sites.

[107] Swarthout R, et al, 2015. Impact of Marcellus Shale Natural Gas Development in Southwest Pennsylvania on Volatile Organic Compound Emissions and Regional Air Quality Environ. Sci. Technol. 2015, 49, 3175−3184

[108] Vinciguerra T et al (2015) Regional air quality impacts of hydraulic fracturing and shale natural

of pollution but no extensive natural gas production. They conclude that a substantial fraction of natural gas is escaping uncombusted, and the signal is detectable hundreds of kilometers downwind. Although ethane is not a criteria pollutant, additional pollutants are likely transported at increasing rates; these could cause ozone and PM to rise and complicate attainment of air quality standards for major urban centers downwind.

147. Field et al 2015 reported numerous localised ozone episodes during the winter of 2011 associated with fugitive emissions of natural gas and condensate.[109]

148. Paulik et al (2015) used passive air samplers to assess levels of 62 PAHs at 23 residential properties in Carroll County Ohio located between 0.04 and 3.2 miles of an active wellpad in early 2014.[110] Sampling sites excluded other sources of PAHs such as urban areas and proximity to airports, and samplers were deployed as far as possible from obvious potential confounding sources. Levels of PAHs were an order of magnitude higher than results previously published for rural areas with a clear pattern of increasing PAH levels with closer proximity to wellpads.

149. Eapi et al (2014) also found substantial variation in fenceline concentrations of methane and hydrogen sulphide, which could not be explained by production volume, number of wells, or condensate volume at natural gas development sites.[111] Two sets of drive-by measurements were taken (the researchers did not have access to the sites) and the study defined 'high' levels as > 3 ppm for methane and > 4.7 ppb (the odour threshold) for H_2S. Elevated levels of methane and/or H_2S were found at 21% of sites (high methane levels at 16.5% of sites and high H_2S at 8% of sites). While mean methane concentrations at dry (where the produced gas is overwhelmingly methane) sites were significantly higher than those at wet sites (where produced gas is comprised of methane and other volatiles such as ethane and butane), no relationship with the size of the site or production volume was found.

150. A study in six counties of the Dallas/Fort Worth areas by Rich et al (2014) assessed chemicals in ambient air samples in residential areas near shale gas wells.[112] Samples were collected using 24-hour passive samplers at 39 locations within 61m of a UNG site from 2008-2010. Approximately 20% of the 101 chemicals identified were designated HAPs, including 1,3-butadiene, tetrachloroethane and benzene (with the latter identified at 76% of sites). Virtually all the analyses detected high methane levels, with the mean level being six times higher than background concentrations. Principal component analysis identified compressors as the dominant source of many of the chemicals, although further studies with larger sample sizes are

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gas activity: Evidence from ambient VOC observations. Atmospheric Environment 110 (2015) 144e150

[109] Field et al 2015. Influence of oil and gas field operations on spatial and temporal distributions of atmospheric non-methane hydrocarbons and their effect on ozone formation in winter. Atmos. Chem. Phys., 15, 3527–3542,

[110] Paulik et al, 2015. Impact of Natural Gas Extraction on PAH Levels in Ambient Air. Environ. Sci. Technol. 2015, 49, 5203−5210

[111] Eapi GR, Sabnis MS, Sattler ML, 2014. *Mobile measurement of methane and hydrogen sulfide at natural gas production site fence lines in the Texas Barnett Shale.* J Air Waste Manag Assoc.64(8): 927-44.

[112] Rich and Orimoloye. Elevated Atmospheric Levels of Benzene and Benzene-Related Compounds from Unconventional Shale Extraction and Processing: Human Health Concern for Residential Communities. *Environmental Health Insights* 2016:10 75–82 doi: 10.4137/EHI.S33314.

required to confirm these findings.

151. In one of the few studies examining air quality before, during and after the development and operation of a fracked gas well pad, Colborn et al (2014) measured levels of VOCs and carbonyls using a monitoring station 1.1 km from the site in Western Colorado over the course of a year.[113] Of the range of chemicals monitored, methane, ethane, propane, toluene, formaldehyde and acetaldehyde were detected in every sample. The highest average levels were for methane, methylene chloride, ethane, methanol, ethanol, acetone, and propane. Chemicals associated with urban traffic emissions as opposed to gas operations such as ethane were found at low levels. There was considerable temporal variability in the number and concentrations of chemicals detected although levels of NMHCs were highest during the initial drilling phase prior to fracturing. These results are noteworthy as they present before and after data.

152. Roy et al (2014) developed an emission inventory to estimate emissions of NOx, VOCs, and $PM_{2.5}$ in Pennsylvania, New York, and West Virginia for 2009 and 2020.[114] The analysis suggested that Marcellus shale development would be an important source of regional NOx and VOCs potentially contributing 12% (6–18%) of emissions in the region in 2020. This level of release was considered large enough to offset projected emissions reductions in other sectors and challenge ozone management in rural areas. While the Marcellus shale was not predicted to contribute significantly to regional $PM_{2.5}$ levels, it could account for 14% (2-36%) of elemental carbon.

153. Gilman 2013 compared VOC concentrations measured at an atmospheric research facility located in the Colorado Wattenberg field with ambient levels monitored in two other NE Colorado sites.[115] VOCs related to oil and natural gas were identified at all three sites and considered to represent a significant source of ozone precursors.

154. Ahmadi and John 2015 conducted a comprehensive analysis of historical ozone data and developed a time series analysis to evaluate the long term relationship between shale gas development and ozone pollution in the Dallas-Fort Worth region of Texas. They also conducted a comparative assessment with an adjacent non-shale gas region. Regional air quality had been extensively monitored for over 30 years and provided an exceptionally comprehensive and extensive dataset. The analysis considered trends during the periods 2000 to 2006 and from 2007 to 2013 and showed that ozone levels decreased in the non-shale gas region compared to the shale gas region. The average long-term component of meteorologically adjusted ozone was 2% higher in the shale gas area from 2008 and the mean short-term meteorologically adjusted ozone was almost 10% higher.

155. Kemball-Cook et al (2010) developed projections of future UNG production in the Haynesville shale under three different intensity conditions based on the number of new wells

[113] Colborn T, Schultz K, Herrick L, Kwiatkowski C. An exploratory study of air quality near natural gas operations. Hum Ecol Risk Assess 2014;20(1):86–105.
[114] Roy et al, 2014. Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas. J Air Waste Manag Assoc. 2014 Jan;64(1):19-37.
[115] Gilman JB, Lerner BM, Kuster WC, de Gouw JA. Source signature of volatile organic compounds from oil and natural gas operations in Northeastern Colorado. Environ Sci Technol 2013;47(3):1297–305

drilled and production estimates for each new active well.[116] These estimates were used to develop emission inventories for each scenario using data from a development in a similar nearby formation. Estimated emissions of NOx, VOCs and CO were large enough to threaten the achievement of proposed ozone standards even in the model assuming limited UNG development. Drill rigs, compressor stations and gas plants were identified as the principal sources of NOx and the authors suggested additional controls on these elements of the process.

Health impacts of pollution

156. Potential hazards only become risks to health if there is exposure to those hazards at levels that might harm health.

157. The number of risk studies is limited and more research is needed to address public concerns about the risks of SGP on human and ecosystem health.[117] [118] A cumulative risk assessment approach would incorporate chemical, physical, and psychosocial stressors that contribute to stress-related health effects in populations living near UNG development sites.[119]

158. Macey et al (2014) assessed concentrations of VOCs in 35 air samples around UNG sites that were collected by trained members of the community in five US states. Residents used an assessment of local conditions to determine the sites of 35 grab samples and supplemented these with 41 formaldehyde badges at production facilities and compressor stations. 46% of the former and 34% of the latter exceeded established air safety standards. High concentrations of benzene, formaldehyde, hexane and H_2S were identified. In some cases, benzene levels exceeded standards by several orders of magnitude.

159. Bunch et al, on the other hand, analysed data from monitors focused on regional atmospheric concentrations in the Barnett Shale region and found no exceedance of health-based comparison values.[120] The study, supported by an industry funded Energy Education Council, concluded that shale gas production activities had not led to VOC exposures of public health concern. The analyses also suggest that VOC levels in general had not increased over time and in some cases had decreased.

160. A study by Zielinska et al (2014) of the impact of SGP on population exposure to air

[116] Kemball-Cook S, Bar-Ilan A, et al (2010). Ozone impacts of natural gas development in the Haynesville Shale. *Environ Sci Technol* **44**(24): 9357–63.
[117] Sexton, K.; Linder, S. H.Cumulative Risk Assessment for Combined Health Effects From Chemical and Nonchemical Stressors Am. J. Public Health 2011, 101 (S1) S81– S88, DOI: 10.2105/ajph.2011.300118
[118] Brittingham, M. Ecological Risks of Shale Gas Development. Risks of Unconventional Shale Gas Development; Washington DC, 2013; http://sites.nationalacademies.org/DBASSE/BECS/DBASSE_083187.
[119] Adgate 2013
[120] Bunch AG, Perry CS, et al, 2014. Evaluation of impact of shale gas operations in the Barnett Shale region on volatile organic compounds in air and potential human health risks. Sci Total Environ 468–469: 832–42.

pollutants in the Barnett Shale region used a combination of active well VOC emission characterisation, pollutant monitoring in a local residential community of 250-300 households in an area of high well density and adjacent to a compressor station, and measurement of the pollutant gradient downwind of a gas well.[121] Monitoring included NOx, NO_2, SO_2, C5– C9 hydrocarbons, carbon disulphide and carbonyl compounds, $PM_{2.5}$ and PAHs. Samples from wellhead condensate tank venting emissions were used to establish a source profile. The average VOC and $PM_{2.5}$ concentrations in the residential area were found to be generally low. However, source apportionment suggested that gas production was significantly contributing to regional VOCs, thought to be caused by increased UNG-related diesel vehicles movements.

161. Litovitz 2013 estimated levels of VOC, NOx, PM_{10}, $PM_{2.5}$ and SO_2 emissions and the cost of the environmental and health damages associated with shale gas extraction in Pennsylvania.[122] While emissions were a small proportion of total statewide emissions, NOx emissions were up to 40 times higher in areas with concentrated shale gas activities than permitted for a single minor source. The estimated environmental and health costs for 2011 ranged from $7.2 to $32 million with over 50% due to compressor stations. The authors emphasise that a substantial proportion of these damages cannot be specifically attributed to shale gas and are less than those estimated for any of the State's large coal power plants. However, despite the uncertainties associated with the estimates, they consider the pollution emissions to be non-trivial.

162. Ethridge et al (2015) reported on extensive monitoring of airborne VOCs in the Barnett Shale region by the Texas Commission on Environmental Quality (TCEQ). TCEQ developed an extensive inventory of emission sources including information on location, type and number of emission sources; equipment and activities conducted; releases to air; and proximity of receptors. A range of monitoring techniques was used to estimate long and short-term exposures in areas with and without UNG during 2009 and 2010. While several short-term samples exceeded odour-based air monitoring comparison values and detected levels above typical background norms downwind of UNG, only three samples exceeded health-based AMCVs. Short-term sampling found elevated levels of VOCs, most notably benzene, being emitted from a small percentage of those facilities.

163. One of the few studies attempting to assess the risk of exposure to air pollution calculated hazard indices (HIs) for residents living <1/2 mile and >1/2 mile from wells.[123] The study used routine ambient air monitoring data from 187 fracking sites from January 2008 to November 2010 AND assumed a cumulative effect from multiple chemicals. The study found that residents living within 0.5 mile of wells were at greater risk than those living > 0.5 mile from wells. For sub-chronic non-cancer conditions this was principally due to exposure to trimethylbenzenes,

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[121] Zielinska et al, 2014. Impact of emissions from natural gas production facilities on ambient air quality in the Barnett Shale area: a pilot study. J Air Waste Manag Assoc. 2014 Dec;64(12):1369-83.

[122] Litovitz A, Curtright A, et al (2013). Estimation of regional air-quality damages from Marcellus Shale natural gas extraction in Pennsylvania. *Environ Res Lett* **8**(1), 014017 doi: 10.1088/1748-9326/8/1/014017.

[123] McKenzie et al, 2012. Human health risk assessment of air emissions from development of unconventional natural gas resources. Science of the Total Environment 424 (2012) 79–87.

xylenes, and aliphatic hydrocarbons. Cumulative cancer risks were 10 in a million for the proximal zone and six in a million in the distal zone, with benzene and ethylbenzene as the major contributor to risk. The largest HI was attributed to the relatively short-term effects of high emissions during the well development and completion period, driven principally by exposure to trimethylbenzenes, aliphatic hydrocarbons and xylenes which have neurological and/or respiratory effects (haematological and developmental effects also contributed to the combined HI). According to PHE, "the paper suggests that the potential risks from sub-chronic exposure are of most concern, especially among residents closest to the well pad".

164. Other risk assessments conducted to date are largely in agreement with these observations, indicating slightly elevated excess lifetime cancer risks driven by benzene, some indication of acute or subchronic non-cancer risks for those living closest to well sites, and little indication of chronic non-cancer risks.[124] [125] [126]

165. A population-based study of the association between ozone levels and health effects in a UNG development region in Wyoming, USA between 2008 and 2011 observed a 3% increase in the number of clinic visits for adverse respiratory-related effects for every 10 ppb increase in the 8 h ozone concentration the previous day.[127]

166. Community-based surveys have documented various symptoms, as well as instances of sleep loss, stress and odour complaints in association with shale gas developments.[128] [129] [130] Though these studies lack scientific rigor because they are small, and use self-selecting or convenience samples of the local population, many of the findings are consistent with the known health effects of exposure to petroleum hydrocarbons.

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[124] Bunch AG, Perry CS, Abraham L, Wikoff DS, et al. Evaluation of impact of shale gas operations in the Barnett Shale region on volatile organic compounds in air and potential human health risks. Sci. Tot. Environ. 2014, 468, 832– 842.

[125] Health Consultation: Public Health Implications of Ambient Air Exposures to Volatile Organic Compounds as Measured in Rural, Urban, and Oil & Gas Development Areas Garfield County, Colorado, Agency for Toxic Substances and Disease Registry; U.S Department of Health and Human Services Agency; Atlanta, GA, 2008; http://www.atsdr.cdc.gov/HAC/pha/Garfield_County_HC_3-13-08/Garfield_County_HC_3-13-08.pdf.

[126] Garfield County Air Toxics Inhalation Screening Level Human Health Risk Assessment: Inhalation of Volatile Organic Compounds Measured In 2008 Air Quality Monitoring Study. Colorado Department of Public Health and Environment: Disease Control and Environmental Epidemiology Division; Rifle, CO, 2010. http://www.garfield-county.com/public-health/documents/6%2030%2010%20%20RisK%20Assessment%20for%20Garfield%20County%20based%20on%202008%20air%20monitoring.pdf

[127] Associations of Short-Term Exposure to Ozone and Respiratory Outpatient Clinic Visits - Sublette County, Wyoming, 2008–2011; Pride, K.; Peel, J.; Robinson, B.; Busacker, A.; Grandpre, J.; Yip, F.; Murphy, T.; State of Wyoming Department of Health: Cheyenne, WY, 2013;

[128] Steinzor, N.; Subra, W.; Sumi, L.Investigating links between shale gas development and health impacts through a community survey project in Pennsylvania New Solutions 2013, 23 (1) 55– 83, DOI: 10.2190/NS.23.1.e

[129] Witter, R. Z.; McKenzie, L. M.; Towle, M.; Stinson, K.; Scott, K.; Newman, L.; Adgate, J. L. Health Impact Assessment for Battlement Mesa, Garfield County Colorado; Colorado School of Public Health, 2011

[130] Saberi, P.Navigating Medical Issues in Shale Territory New Solutions 2013, 23 (1) 209– 221.

167. A self-reporting survey of 108 individuals from 55 households in 14 counties in Pennsylvania between August 2011 and July 2012 found over 50% of participants reporting various respiratory, behavioural, neurological, muscular, digestive, skin and vision symptoms; some of which were associated with proximity to fracking and experience of odours. The same study conducted 34 air tests and 9 water tests in a subset of 35 households. 19 air samples recorded a variety of VOCs and BTEX levels higher than those previously reported by the local Department for Environmental Protection; and 26 chemicals detected in 11 well water samples which exceeded the MCL for manganese, iron, arsenic, or lead. There was some congruence between symptoms and chemicals identified by environmental testing, but the study was small and did not involve a random sample of participants.[131]

168. A cross sectional study of patients presenting to a primary care centre in Pennsylvania by Saberi (2014) used a self-administered questionnaire to explore attribution of health perceptions and 29 symptoms to environmental causes including UNG over one week in 2012. Of the 72 participants, 42% attributed at least one symptom to an environmental cause with 22% identifying UNG development. 22% of respondents linked a health problem to natural gas (16 of 72), however some of these symptoms are of dubious plausibility. Nine of the 16 linked natural gas to a 'medical symptom', a reduced list of 15 drawn from the 29 in the questionnaire. Case reviews were conducted on six participants linking 'medical symptoms' to natural gas and only one had a record of both the symptom and the concern and in three cases there was no record of either. There was no measure of potential exposure and while mapping of 74% of respondents showed residence within two miles of a well, it also demonstrated no evidence of clustering. The potential for bias is reflected in the high levels of symptom linkage to other environmental issues such as antibiotics in food (22%) and ageing due to free radicals (11%).

169. Steinzor et al (2013) reported a questionnaire based community health survey supplemented with environmental data (VOCs in air and heavy metals in well water) from sites close to participants' homes.[132] This study involved 108 individuals including people recruited at public events from 14 Pennsylvania counties. All interviewees reported symptoms (range 2-111) with over 50% reporting more than 20. A variety of symptoms was identified including respiratory, behavioural, neurological, muscular, digestive, skin and vision symptoms. Throat and sinus issues increased with residential proximity to UNG sites and an association between odours and some symptoms was also identified. There is likely bias in the selection of study subjects and while some environmental data were collected, this study used distance as a proxy for exposure. 34 air and nine water samples were taken at 35 households; locations were selected based on household interest, severity of reported symptoms, and proximity to gas facilities. 19 air samples recorded a variety of VOCs and while BTEX levels were higher than those previously reported in samples taken by the local Department for Environmental

[131] Ferrar KJ; Kriesky J; Christen CL, Marshall LP, Malone SL, et al. Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region Int. J. Occup. Environ. Health 2013, 19 (2) 104– 12, DOI: 10.1179/2049396713y.0000000024

[132] Steinzor N, Subra W and Sumi L (2013). Investigating links between shale gas development and health impacts through community survey project in Pennsylvania. *New Solut* **23:** 55–83.

Protection and used as controls, no comparisons with regulatory or advisory standards were made. 26 chemicals were detected in well water with 11 samples exceeding the MCL for manganese, iron, arsenic, or lead. While the study reports some congruence between symptoms and chemicals identified by environmental testing all the symptoms were self-reported, mostly highly non-specific and cannot be confidently linked to emissions from UNGD sites.

170. The West Virginia Natural Gas Horizontal Well Control Act of 2011 requires determination of the effectiveness of a 625 foot set-back from the center of the pad of a horizontal well drilling site. An investigation which collected data on dust, hydrocarbon compounds and radiation to characterize levels that might be found at 625 feet from the well pad center of unconventional gas drilling sites found detectable levels of dust and VOCs with some benzene concentrations above what the CDC calls the "the minimum risk level for no health effects." But there were no concerns found related ionizing radiation levels from airborne particulate matter.[133]

171. A retrospective study of 124,862 births in rural Colorado indicated an association between maternal proximity to natural gas well sites and birth prevalence of congenital heart defects and neural tube defects, but no association with oral clefts, term low birth weight or preterm birth.[134] Exposure was imputed by calculating tertiles of inverse distance weighted natural gas well counts within a 10-mile radius of maternal residence (range 1 to 1400 wells per mile) and a reference population with no wells within 10 miles. Associations were examined using logistic regression and multiple linear regression. The number of births was approximately equal in exposed/non-exposed groups. Prevalence of CHDs increased with exposure tertile with an OR in highest tertile of 1.3 (CI 1.2, 1.5). NTD prevalence was also associated with the highest tertile (OR 2.0; CI 1.0, 3.9), compared with the non-exposed group. Exposure was negatively associated with prematurity and low birthweight and there was a modest positive association with foetal growth. No association was reported for oral clefts. This well conducted analysis of a large population suggests a positive association between proximity and density of gas wells in relation to mothers' residence and an increased prevalence of CHDs and possibly NTDs. This type of study has several recognised limitations, which the authors acknowledge, including incomplete data, undercounting, the effect of folic acid supplements, residual confounding and lack of exposure measures. Again the authors call for further research addressing these issues.

172. A working paper exploring 1,069,699 births in Pennsylvania reported increased prevalence of low birthweight and small for gestational age births, as well as reduced appearance, pulse, grimace, activity, respiration (APGAR) scores in infants born to mothers living within 2.5 km of a natural gas well compared to infants born to mothers living further than 2.5 km from a well.[135]

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[133] McCawley M, 2013. Air, Noise, and Light Monitoring Results for Assessing Environmental Impacts of Horizontal Gas Well Drilling Operations (ETD-10 Project. http://wvwri.org/wp-content/uploads/2013/10/a-n-l-final-report-for-web.pdf

[134] McKenzie L.M, Guo R, Witter RZ, et al, 2014. Maternal residential proximity to natural gas development and adverse birth outcomes in rural Colorado Environ. Health Perspect. DOI: 10.1289/ehp.1306722

[135] Hill, E. Unconventional Natural Gas Development and Infant Health: Evidence from Pennsylvania. Cornell University: Working Paper, Charles Dyson School of Applied Economics and Management, 2012

173. A study of childhood cancers before and after fracking in Pennsylvania found no difference in the incidence rate, except for CNS tumours although no relationship was apparent with the number of wells drilled. The study found a higher incidence of total cancers for counties with 500 wells or fewer compared to counties with more than 500 wells. The period of data analysis after drilling was generally too short for an adequate assessment of cancer risks, given latency in cancer development.[136] The authors recognise that SIRs should not be directly compared but actually do so to make reassuring conclusions. This has been challenged on other key methodological issues by others.[137]

174. Few studies have attempted to use biomonitoring to explore risks from shale gas-related pollutants. Blood and urine samples collected from 28 adults living in Dish, Texas, a town with large numbers of gas wells, storage tanks, and compressor stations near residences, found no indication of community wide-exposure to VOCs.[138] These results likely reflect the multiple potential sources and the short half-lives of most VOCs in urine and blood, especially since the sampling did not coincide with known or perceived exposures, and concurrent air samples were not collected for study subjects.

175. Rich et al (2016) found elevated atmospheric levels of carbon disulphide (CS2) and 12 associated sulfide compounds present in the atmosphere in residential areas where UOG extraction and processing operations were occurring. Atmospheric chemical concentrations were compared to the U.S. Environmental Protection Agency (EPA) Urban Air Toxics Monitoring Program (UATMP), results, indicating that atmospheric CS2 concentrations in the study areas exceeded the national maximum average by 61% (2007), 94% (2008–2009), 53,268% (2010), 351% (2011), and 535% (2012)" above national background levels. Literature regarding evidence of health effects of CS2 on glucose metabolism was also reviewed, potential complications including diabetes, neurodegenerative disease, and retinopathy. *'Complaints of adverse health effects related to UOG emissions were found to be consistent with CS2 exposure. However, air monitoring analysis found multiple volatile organic compounds present simultaneously with CS and sulphide chemicals; therefore, it is difficult to determine which chemical or chemicals were the initiator of the health complaints'[139].*

176. Jemielita et al (2015) examined the relationship between inpatient rates and well numbers and density (wells per km^2) in three Pennsylvania counties for 2007-2011.[140] There had been a

[136] Fryzek J.; Pastula, S.; Jiang, X.; Garabrant, D. H. Childhood cancer incidence in Pennsylvania counties in relation to living in counties with hydraulic fracturing sites J. Occup. Environ. Med. 2013, 55 (7) 796– 801
[137] Goldstein D, Malone, S. Obfuscation Does Not Provide Comfort: Journal of Occupational and Environmental Medicine. 2013. 55(11); 1376–1378).
[138] DISH, Texas Exposure Investigation; Texas Department of State Health Services: Dish, Denton County, TX, 2010; www.dshs.state.tx.us/epitox/consults/dish_ei_2010.pdf.
[139] Rich et al, 2016, Carbon Disulfide (CS2) Interference in Glucose Metabolism from Unconventional Oil and Gas Extraction and Processing Emissions, *Environmental Health Insights* 2016:10 51–57 doi: 10.4137/EHI.S31906.
[140] Jemielita T, Gerton GL, Neidell M, Chillrud S, Yan B, Stute M, et al. (2015) Unconventional Gas and Oil Drilling Is Associated with Increased Hospital Utilization Rates. PLoS ONE 10(7): e0131093. doi:10.1371/journal.pone.0131093

large increase in UNG development in two of the counties during this period and none in the third county. The study found that cardiology inpatient prevalence rates were significantly associated with well numbers ($p<0.00096$) and well density ($p<0.001$) and neurology inpatient prevalence rates were also significantly associated with density ($p<0.001$). While this study involved a large resident population, there are limitations which are recognised by the authors. While population demographics were similar by county there was no analysis by zip code and no control for smoking, a key confounder for cardiology inpatient prevalence. Most wells appear to have been established in last year of study which covered a relatively short period and there was considerable variation in the number of wells by zip code adding to the potential for exposure misclassification.

177. Casey et al (2015) examined the relationship between four adverse reproductive outcomes and proximity to UNG and level of drilling activity in a retrospective cohort study using data on over 9,000 mothers linked to almost 11,000 neonates over four years.[141] Multilevel linear and logistic regression models explored associations between a UNG activity index and birthweight, preterm birth, 5-minute Apgar scores, and small for gestational age (SGA). An strong association between UNG activity and preterm birth was identified, but not with the other outcomes. A post hoc analysis also identified an association with physician recorded high-risk pregnancy (OR 1.3 95% CI 1.1, 1.7). While this study controlled for a number of confounding factors, there is potential for residual confounding and the lack of exposure measures inevitably increases the risk of exposure misclassification.

178. Stacy et al (2015) examined the association of proximity to UNG with birthweight, SGA and prematurity in SW Pennsylvania for the period 2007-2010.[142] This study, which included over 15,000 live births, found lower birth weight in the 'most exposed' compared with the 'least exposed' populations and a significantly higher incidence of SGA (OR 1.34; 95% CI 1.10–1.63). There was no significant association with prematurity.

179. Rabinowitz (2015) conducted a household survey of residents' self-reported symptoms and views on environmental quality in Washington County Pennsylvania in 2012 during a period in which there were 624 active wells (95% first drilled between 2008-12). Homes were visited to establish access to ground-fed water wells and households classified according to distance from the nearest well: < 1 km, 1–2 km, or > 2 km.[143] After adjustment for age, sex, household education level, smokers in household, job type, animals in household, and awareness of environmental risk, household proximity to wells remained associated with the number of symptoms reported per person < 1 km ($p = 0.002$) and 1–2 km ($p = 0.05$) compared with > 2 km from gas wells respectively. Living in a household < 1 km from the nearest well remained

[141] Casey JA, et al, 2016. Unconventional natural gas development and birth outcomes in Pennsylvania, USA. *Epidemiology*. 2016 March ; 27(2): 163–17

[142] Stacy SL, Brink LL, Larkin JC, Sadovsky Y, Goldstein BD, Pitt BR, et al. (2015) Perinatal Outcomes and Unconventional Natural Gas Operations in Southwest Pennsylvania. PLoS ONE 10(6): e0126425. doi:10.1371/journal.pone.0126425

[143] Rabinowitz et al, 2015. Proximity to Natural Gas Wells and Reported Health Status: Results of a Household Survey in Washington County, Pennsylvania. Environmental Health Perspectives volume 123 (1):

associated with increased reporting of skin conditions (OR= 4.13; 95% CI: 1.38, 12.3) and upper respiratory symptoms (OR = 3.10; 95% CI: 1.45, 6.65) when compared to households > 2 km from the nearest gas well. Environmental risk awareness was also significantly associated with reports of all groups of symptoms. The sample size is small in epidemiological terms and is also limited by the self reported nature of the symptoms, potential bias and lack of direct exposure measures and the issue of multiple testing.

180. Bamberger and Oswald (2012) used an ecological study with interviews of farmers and families from six US states together with limited exposure, diagnostic and toxicological data.[144] The families were referred by environmental groups or activists and associated with seven conventional well sites and 18 HVHF sites. The researchers also conducted two opportunistic natural experiments where livestock had been exposed and non-exposed on the same farms. Exposures were alleged to have occurred through contamination of water. Virtually all health data were self-reported and included a wide range of symptoms for humans (neurological, GI, dermatological, headaches, nosebleeds, fatigue and backache) and animals (mortality, reproductive, neurological, GI, and dermatological symptoms). Outcomes reported for the two natural experiments included 21/60 cattle exposed to fracking fluid having died and 16 having failed to calve versus zero deaths and one failure to calve in the 36 non-exposed cattle (no significance levels reported). Twenty-one of the interviewees were followed up 15-34 months after the initial interview and questioned about subsequent exposures and health effects. There were no significant health changes reported by those living in areas where industry activity had either increased or remained constant. Where industry activity had decreased the total number of reported symptoms in humans and animals also decreased.

181. A Health Impact Assessment conducted by Witter (2013) following concerns reported by communities in Battlement Mesa estimated an increased risk of non-cancer health effects from subchronic VOC exposures during the well completion period and a small increased lifetime excess cancer risk (10 x 10−6) for those living close to wells compared to those living farther from wells (6 x10−6).[145] Self-reported short term symptoms such as headaches, nausea, upper respiratory irritation and nosebleeds in residents living within a half mile of well development were considered plausibly associated with odour events.

182. Having determined that households in proximity to gas wells in Ohio were exposed to higher levels of PAHs, Paulik et al (2015) used quantitative risk assessment to estimate the excess lifetime cancer risks for residents and workers associated with the recorded levels of PAHs and found that the risk in the proximal residential exposure group exceeded the EPA acceptable range and was 30% higher compared to the distal population (0.04 cf 3.2 miles).[146]

[144] Bamberger and Oswald (2012) Impacts of gas drilling on animal and human health. NEW SOLUTIONS, Vol. 22(1) 51-77, 2012
[145] Witter RZ, McKenzie L, et al (2013). The use of health impact assessment for a community undergoing natural gas development. *Am J Pub Health* **103**(6): 1002–10.
[146] Paulik et al, 2015 Impact of Natural Gas Extraction on PAH Levels in Ambient Air. Environ. Sci. Technol. 2015, 49, 5203−5210

Hazards and risks associated with traffic, noise, light and odour

183. SGP involves continuous activity conducted over the entire course of a day, seven days a week, for a sustained period of time.[147] The noise of compressors, generators and drilling; extensive truck movements; intrusive un-natural lighting overnight; and the release of bad smelling chemicals, can have significant negative health and wellbeing impacts on nearby communities, especially in the context of quiet rural and semi-rural areas.

184. SGP in the UK is expected to be sited close enough to a mains water supply and gas distribution network which will considerably reduce the number of truck movements compared to many operations in the US. Nonetheless, truck-heavy traffic is still required to construct wellpads (including ancillary infrastructure such as offices, generators, compressors and tanks), drill the boreholes, and transport fracking fluid, silica and wastewater.

185. The amount of traffic affecting any given area involved will depend on the number of wellpads and boreholes in that area, and the volume of wastewater needing to be transported away. The Institution of Civil Engineers estimated that a single well might require between 500 and 1,250 HGV lorry movements.[148] The Royal Society for the Protection of Birds give a figure of between 4,300 and 6,600 truck trips per well pad.[149] As noted earlier, Watson estimated that the volume of fluid needing treatment from two exploratory fracking sites in Lancashire would involve about 1,440 tankers with a capacity of 35,000 litres (360 tanker loads per well) and a total tanker mileage of 470,000 miles.

186. Potential adverse impacts from truck traffic include congestion; road traffic accidents (with potential spills of hazardous materials); as well as damage to roads, bridges and other infrastructure. One study from the US reported that automobile and truck accident rates were between 15% and 65% higher in counties with shale gas drilling compared to those without, including an associated increase in traffic fatalities.[150]

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[147] The typical lifetime for a well is variable and not well established; but it seems to range from about two to five years depending on how much the shale is re-worked and the well re-fracked.

[148] Institution of Civil Engineers. Written Submission, Environmental Audit Committee: Environmental Risks of Fracking Enquiry (FRA070), para 2.1

[149] Royal Society for the Protection of Birds. Written Submission to Environmental Audit Committee: Environmental Risks of Fracking Enquiry (FRA015), para 3.6

[150] Graham J, Irving J, Tang X, Sellers S, et al. (2015). Increased Traffic Accident Rates Associated with Shale Gas Drilling in Pennsylvania. *Accident Analysis and Prevention*, 74:203–209.

187. In the Bakken shale region, there was an increase of 68% of crashes involving trucks from 2006 to 2010.[151] In the Eagle Ford region, the Texas Department of Transportation reported a 40% increase in fatal motor vehicle accidents from 2008 to 2011.[152] Likewise, the Crash Reporting System from the Pennsylvania Department of Transportation reported an increase in accidents involving heavy trucks between 1997 and 2011.[153] Some data from Pennsylvania indicate that between 1997 and 2011, counties with a relatively large degree of shale gas development experienced a significant increase in the number of total accidents and accidents involving heavy trucks compared to counties with no shale gas development.[154]

188. Noise, smells and intrusive lighting are also potential hazards associated with SGP.

189. Such nuisances are well recognised as health hazards and potentially serious interferences to normal day-to-day living.[155] [156] [157] The stress and loss of sleep that may be caused by nuisances such as traffic congestion, noise and light pollution are forms of ill health in their own right, but are also factors in the genesis of a range of other diseases and illnesses.[158] [159]

190. A Health Impact Assessment conducted by Witter (2013) following concerns reported by communities in Battlement Mesa found that increased traffic would increase the risk of accidents and reduce levels of walking and cycling. Recorded noise levels and complaint data suggested that noise levels related to the site could be in the range associated with health impacts.[160] The paper also reported a 15% reduction in property values in the vicinity of the site and postulated that anxiety and stress levels would be increased as a result of community concerns.

191. The effects of a nuisance are source dependent, meaning that objective measures of nuisance are not sufficient to gauge its potential effect. The source and underlying cause of the nuisance is an important influence on the type and degree of impact of that nuisance.

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[151] Ridlington E and Rumpler J, 2013. Fracking by the Numbers. Environment America Research & Policy Center. http://www.environmentamerica.org/reports/ame/fracking-numbers

[152] Increased Traffic, Crashes Prompt New Campaign to Promote Safe Driving on Roadways Near Oil, Gas Work Areas; Texas Department of Transportation: Austin, TX, 2013; http://www.txdot.gov/driver/share-road/be-safe-drive-smart.html.

[153] Adgate JL, Goldstein BD and McKenzie LM, 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. Environ. Sci. Technol 48 (15), pp 8307–8320

[154] Muehlenbachs, L.; Krupnick, A. J. Shale gas development linked to traffic accidents in Pennsylvania. Common Resources. 2013; http://common-resources.org/2013/shale-gas-development-linked-to-trafficaccidents-in-pennsylvania/

[155] https://www.gov.uk/statutory-nuisance

[156] WHO/European Commission. Burden of disease from environmental noise. Quantification of healthy life years lost in Europe. The WHO European Centre for Environment and Health, Bonn Office, WHO Regional Office for Europe . ISBN: 978 92 890 0229 5 2011

[157] http://ec.europa.eu/health/scientific_committees/opinions_layman/artificial-light/en/l-2/4-effects-health.htm#1

[158] Battlement Mesa Health Impacts Assessment (Colorado, USA). Available at http://www.garfield-county.com/environmental-health/battlement-mesa-health-impact-assessment-ehms.aspx

[159] Gee GC, Payne-Sturges DC, 2004. Environmental Health Disparities: A Framework Integrating Psychosocial and Environmental Concepts. Environ Health Perspect. 112(17): 1645–1653

[160] Witter RZ, McKenzie L, et al (2013). The use of health impact assessment for a community undergoing natural gas development. *Am J Pub Health* **103**(6): 1002–10.

192. The amount of stress that will be experienced by individuals and communities affected by SGP cannot be predicted with precision, but will clearly depend on the scale of SGP and the size and proximity of surrounding communities.

193. When considering the health impacts of noise from a given source, the volume and intensity of the noise, whether it is prolonged and continuous, how it contrasts with the ambient noise levels, and the time of day must be taken into account. Noise levels depend not only on the source, but also on other factors such as distance from the source, air temperature, humidity, wind gradient, and the topography.

194. Both the sound level of the noise (objective noise exposure) and its subjective perception can influence the impact of noise on neuroendocrine homeostasis.[161] In other words, noise exposure can lead to adverse health outcomes through direct and indirect pathways. Non-physical effects of noise are mediated by psychological and psycho-physiological processes.[162] Noise annoyance may produce a host of negative responses, such as feeling angry, displeasure, anxious, helpless, distracted and tired.[163] [164]

195. Sleep disturbance is another common response among populations exposed to environmental noise, and is associated with negative impacts on both health and quality of life.[165] Meaningful levels of sleep fragmentation and deprivation can adversely affect both physical and mental health, and are often considered the most severe non-auditory effect of environmental noise exposure.[166]

196. According to Goodman et al (2016), the local impacts of a single well pad on traffic may be of short duration but large magnitude.[167] They also note that the effects of SGP on surrounding communities will vary over time. For example, while excess noise emissions may appear negligible (b1 dBA) when normalised over the completion period, they may be considerable (+3.4 dBA) during particular hours, especially at night.

197. An investigation which collected data on noise levels at 625 feet away from the well pad center of unconventional gas drilling sites in West Virginia found that average noise levels for the

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[161] Munzel, T., T. Gori, W. Babisch, and M. Basner (2014), Cardiovascular Effects of Environmental Noise Exposure. Eur Heart J., 35, 829–836; doi:10.1093/eurheartj/ehu030.

[162] Shepherd, D., D. Welch, K.N. Dirks, and R. Mathews (2010), Exploring the Relationship between Noise Sensitivity, Annoyance and Health-Related Quality of Life in a Sample of Adults Exposed to Environmental Noise. Int J. Environ Res Public Health, 7, 3579–3594; doi:10.3390/ijerph7103580

[163] Babisch, W. (2002), The Noise/Stress Concept, Risk Assessment and Research Needs. Noise Health, 4, 1–11.

[164] Babisch, W., G. Pershagen, J. Selander, D. Houthuijs, O. Breugelmans, E. Cadum, et al. (2013), Noise Annoyance — A Modifier of the Association between Noise Level and Cardiovascular Health? Science of The Total Environment, 452–453, 50–57; doi:10.1016/j.scitotenv.2013.02.034.

[165] Muzet, A. (2007), Environmental Noise,Sleep and Health. Sleep Medicine Reviews, 11, 135–142; doi:10.1016/j. smrv.2006.09.001

[166] Hume, K.I., M. Brink, and M. Basner (2012), Effects of Environmental Noise on Sleep. Noise Health, 14, 297–302; doi:10.4103/1463-1741.104897.

[167] Goodman et al, 2016 Investigating the traffic-related environmental impacts of hydraulic-fracturing (fracking) operations, Environment International 89–90 (2016) 248–260

duration of work at each site were not above the recommended 70dBA level recommended by the EPA for noise exposure, but that noise at some locations was above the local limits set by some counties and cities.[168]

Social, economic and ecological effects

198. Shale gas production can produce positive health effects in local communities through social and economic pathways by generating new investment, profits and employment. Evidence from the US shows various forms of economic benefit associated with the shale gas boom.

199. It is less commonly understood that SGP also produces social and economic dis-benefits and can impact negatively on health by disrupting the social fabric of local communities, harming *other* economic activity, and damaging public infrastructure.

200. A health impact assessment of proposed shale gas development in Garfield Country, conducted by the Colorado School of Public Health noted that the proposal itself had already caused "additional stress" associated with: the social effects of prospective industrial activity in a non-industrial area; perceived loss of shared community ideals and cohesion; declining property values; and worries about possible impacts on the education system, population numbers, demographics and customs.[169] It also noted that community impacts of the natural gas industry boom of 2003-2008 and subsequent decline in 2009 elsewhere in the state had included "increased crime and sexually transmitted diseases, declining property values and impacts on the educational environment".

201. A review of risks to communities from shale energy development by Jacquet (2014) notes that the introduction of temporary but intensive extractive industries into an area can produce benefits in the form of new jobs and increased local revenue, but also bring a variety of social and health harms. Among the effects with negative impacts are an influx of temporary workers (often predominantly composed of young men) undermining community cohesion, increasing the cost of living, and raising levels of alcohol and drug use, mental illness and violence.[170]

[168] McCawley M, 2013. Air, Noise, and Light Monitoring Results for Assessing Environmental Impacts of Horizontal Gas Well Drilling Operations (ETD-10 Project. http://wvwri.org/wp-content/uploads/2013/10/a-n-l-final-report-for-web.pdf

[169] Battlement Mesa Health Impacts Assessment (Colorado, USA). Available at http://www.garfield-county.com/environmental-health/battlement-mesa-health-impact-assessment-ehms.aspx

[170] Jacquet J, 2009. Energy boomtowns and natural gas: Implications for Marcellus Shale local governments and rural communities. The Northeast Regional Center for Rural Development: University Park, PA,. Available from: http://aese.psu.edu/nercrd/publications/rdp/rdp43/view.

202. Similar findings have been found in other studies.[171] [172] [173] The extraction of non-renewable natural resources such as natural gas is typically characterized by a "boom-bust" cycle: after the boom period of the initial construction and drilling phases, there is a decline in well-paying, stable jobs during the production phase.

203. Increased pressure on local public services can also precipitate negative knock-on effects. Anecdotal evidence from the US notes that the shale gas industry has led to local municipalities being subjected to a range of demands for additional or new services, and that the administrative capacity, staffing levels, equipment, and outside expertise needed to meet those demands can be beyond the available public budgets.[174]

204. One critical area of impact has been on local roads and bridges which are damaged and worn down by the heavy traffic associated with shale gas. In the Barnett Shale region of Texas, it has been reported that early deterioration of city streets has increased the burden on taxpayers because, even though access roads to the well sites are built and maintained by the operators, many of the journeys made by the trucks were on public roads that were not designed to withstand the volume or weight of this level of truck traffic.[175]

205. The regulatory burden of fracking may also be considerable and place a squeeze on the budgets of local municipalities and regulatory agencies. In the US, public authorities have had to bear the cost of the required expertise, administration, monitoring, and enforcement capacity. Likewise, health services and Public Health departments must be prepared to receive and respond to incident reports and citizen concerns about environmental health issues.

206. The scale and nature of the social and economic effects of SGP will be context specific. For some members of a community, shale gas may improve social and economic wellbeing, while for others it may do the opposite.

207. Importantly, levels of stress and community division (and consequent negative mental health effects) are amplified when levels of trust and transparency concerning industry and government action are low.[176]

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[171] Adgate J, Goldstein B, McKenzie L, 2014. Potential Public Health Hazards, Exposures and Health Effects. Environ. Sci. Technol. 48 (15): 8307-8320. Doi: 10;1021/es404621d.
[172] House of Representatives Standing Committee on Regional Australia. 2013. Cancer of the bush or salvation for our cities? Fly-in, fly-out and drive-in, drive-out workforce practices in regional Australia. Canberra: Commonwealth of Australia. http://www.aph.gov.au/parliamentary_business/committees/house_of_representatives_committees?url=ra/fifodido/report.htm
[173] Hossain D, Gorman D, Chapelle B, et al. Impact of the mining industry on the mental health of landholders and rural communities in southwest Queensland. *Australas Psychiatry* 2013; 21: 32-37.
[174] Christopherson and Rightor, 2011. How Should We Think About the Economic Consequences of Shale Gas Drilling? Cornell University
[175] Christopherson and Rightor, 2011. How Should We Think About the Economic Consequences of Shale Gas Drilling? Cornell University
[176] Ferrar K, Kriesky, Christen C, Marshall L et al, 2013. Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region. Int. *J. Occup. Environ. Health 2013*. 19 (2): 104–12. Doi: 10.1179/2049396713y.0000000024.

208. As part of a health impact assessment in Lancashire related to two exploratory faking applications, the Director of Public Health noted that the main risks of the proposed projects were "a lack of public trust and confidence, stress and anxiety from uncertainty that could lead to poor mental well-being, noise-related health effects due to continuous drilling and issues related to capacity for flow-back wastewater treatment and disposal".[177]

209. This includes the contentious and divisive nature of SGP within the community causing stress, anxiety and illness already being experienced by local communities. In the Health Impact Assessment, the Director of Public Health reported that: *"The over-riding responses about the two proposed exploration sites voiced by members of the local communities who attended the workshops were those of fear, anxiety and stress, which are affecting their mental wellbeing, with some people experiencing sleep disturbance and depression".*[178]

210. Shale gas production is also a spatially intense activity that can alter the character and aesthetic of the surrounding landscape, affect wildlife and biodiversity, and cause habitat fragmentation. According to Ingraffea et al "economic development of gas and oil from shale formations requires a high well density, at least one well per 80 surface acres, over large continuous areas of a play".[179]

211. Lave and Lutz (2014) considered that while the landscape disturbance of UNG sites is relatively small compared with other land use activities, fragmentation of ecosystems was extensive. This necessitates further research to better protect important habitats.[180]

212. The social, health and economic impact of losing or damaging green space and 'ecosystem services', including damage to leisure and tourism, needs to be considered. The potential erosion of the intrinsic value of the natural integrity and beauty of the environment should also be considered.

213. The health benefit of the availability and access to green spaces has been documented.[181] [182] These are concerns associated with all types of energy development (including solar and wind).

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[177] Lancashire County Council, 2014. Potential health impacts of the proposed shale gas exploration sites in Lancashire. Minutes, http://council.lancashire.gov.uk/ieIssueDetails.aspx?IId¼29552&PlanId¼0&Opt¼3#AI22656

[178] Ben Cave Associates. Overview report on HIA work concerning planning applications for temporary shale gas exploration: health impact assessment support, shale gas exploration. Lancashire County Council, 2 September. Leeds: Ben Cave Associates Ltd., 2014, http://bit.ly/1BsZ3Au

[179] Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012

[180] Lave and Lutz, 2014. Hydraulic Fracturing: A Critical Physical Geography Review. Geography Compass 8/10: 739–754, 10.1111/gec3.12162

[181] Mitchell R, Popham F, 2008. Effect of exposure to natural environment on health inequalities: an observational population study. *The Lancet*. 372: 1655-1660. Doi: 10.10166/50140-6736(08)61689-x.

[182] CABE, 2010. Community green: using local spaces to tackle inequality and improve health. London. Available from: http://www.openspace.eca.ed.ac.uk/pdf/appendixf/OPENspacewebsite_APPENDIX_F_resource_1.pdf.

214. There is some, but limited, literature assessing the ecological impacts of shale gas development in the US.[183] [184] [185] [186] [187] [188] [189] [190] [191] Some adverse effects on agro-ecosystems and animal husbandry have also been identified.[192]

215. Another concern is the use of considerable quantities of water posing localised risks to water supplies.[193] There are many figures used to describe the amount of water required for SGP. The average estimated water usage for drilling and hydraulic fracturing a well in the Marcellus Shale is said to range from 13,000 m3 to 21,000 m3 with limits of 9,000 m3 to 30,000 m3 for a typical 1,200m horizontal well.[194] According to the UK Shale Gas Task Force, a well needs between 10,000 and 30,000 m3 (10,000 to 30,000 tonnes or two to six million gallons) of water over its lifetime. The Institution of Civil Engineers, in a written submission to Environmental Audit Committee, gave a figure of 10,000 to 25,000 m^3.

216. The amount of water used per well varies depending on geological characteristics, well construction (depth and length) and fracturing operations (chemicals used and fracture stimulation design).[195] [196] Of the total water, 10% is used for drilling, 89% for fracking, and the rest

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183 Jones NF and Pejchar L, 2013. Comparing the ecological impacts of wind and oil & gas development: a landscape scale assessment. PLoS ONE 8 (11), e81391.

184 Jones I, Bull J, Milner-Gulland E, Esipov A, Suttle K, 2014. Quantifying habitat impacts of natural gas infrastructure to facilitate biodiversity offsetting. *Ecol. Evol*. 4 (1): 79–90. Doi: 10.1002.ece3.884.

185 Souther S, Tingley M, Popescu V, Hayman et al, 2014. Biotic impacts of energy development from shale: research priorities and knowledge gaps. *Front. Ecol. Environ*. 12 (6): 330–338. Doi: 10.1890/130324.

186 Hamilton L, Dale B, Paszkowski C, 2011. Effects of disturbance associated with natural gas extraction on the occurrence of three grassland songbirds. *Avian Conserv.Ecol*. 6 (1): 7. Doi: 10.5751:ACE-00458-060107.

187 Papoulias D, Velasco A, 2013. Histopathological analysis of fish from Acorn Fork Creek, Kentucky, exposed to hydraulic fracturing fluid releases. *Southeast. Nat*. 12 (sp4): 92–111.Doi: 10.1656/0(!.012s413.

188 Weltman-Fahs M, Taylor J, 2013. Hydraulic fracturing and brook trout habitat in the Marcellus Shale region: potential impacts and research needs. *Fisheries*. 38 (1): 4–15. Doi: 10.1080/03632415.2013.750112.

189 Brittingham M, Maloney K, Farag A, Harper D, Bowen Z, 2014. Ecological risks of shale oil and gas development to wildlife, aquatic resources and their habitats. *Environ. Sci. Technol.* 48 (19):11034–11047.

190 Racicot A, Babin-Roussel V, Dauphinais J, Joly J-S et al, 2014. A framework to predict the impacts of shale gas infrastructures on the forest fragmentation of an agroforest region. *Environ. Manag*. 53 (5): 1023–1033. Doi: 10.1007/s00267-014-0250-x.

191 Kiviat E, 2013. Risks to biodiversity from hydraulic fracturing for natural gas in the Marcellus and Utica shales. *Ann N Y Acad Sci*. 1286: 1–14. Doi: 10.1111/nyas.12146.

192 Bamberger M, Oswald RE, 2012. Impacts of Gas Drilling on Human and Animal Health. New Solutions 22, 51–77.

193 Chartered Institute of Environmental Health (CIEH) and Scientists for Global Responsibility (SGR) 21/7/2014 'Shale Gas and fracking - examining the evidence'

194 New York State Dept. of Environmental Conservation. Preliminary Revised Draft Supplemental Generic Environmental Impact Statement of the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs. October 5, 2009. Revised July 2011.

195 Freyman, M., 2014 Hydraulic fracturing & water stress: water demand by the numbers (2014) http://www.ceres.org/issues/water/shale-energy/shale-and-water-maps/hydraulic-fracturing-water-stress-water-demand-by-the-numbers (accessed 10.20.14)

196 Torres Yadav and Khan 2016. A review on risk assessment techniques for hydraulic fracturing water and produced water management implemented in onshore unconventional oil and gas production. Science of the Total Environment 539 (2016) 478–493

is consumed by infrastructure. In regions where local, natural water sources are scarce or dedicated to other uses, the limited availability of water may be a significant impediment to gas resource development.[197] [198]

217. According to Broderick et al (2011), the entire multi-stage fracturing operation for a single well requires around 9,000-29,000m^3.[199] For all fracturing operations carried out on a six well pad, a total of between 54,000-174,000m^3 of water would be required for a first hydraulic fracturing procedure. They also estimate that in order to provide 9bcm/year of shale gas for 20 years in the UK, an estimated 25-33 million cubic metres of water is required. Averaged over the 20 year period, this is equivalent to an annual water demand of 1.25 to 1.65 million cubic metres. This compares with current levels of abstraction by industry (excluding electricity generation) of 905 million cubic metres. This, although the volume of water used per well sounds large, when set in the context of overall water supply and use in other industries it is not.[200] Nonetheless, a large number of active wells within an area may have the potential to stress available water supplies.

218. Both the economic and commercial viability and benefits of shale gas production are dependent on a range of variables including the actual productivity of the wells, future energy market conditions, and the policy / regulatory environment within which natural gas is extracted. Production in shale plays is unpredictable and only a small number of wells may be able to produce commercial volumes of gas over time without re-fracking, which is very costly.

219. The claims of economic development and public benefit need to be looked at carefully because they are often produced by those with a vested interest and are based on optimistic assumptions.

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[197] STUART M E. 2011. Potential groundwater impact from exploitation of shale gas in the UK. *British Geological Survey Open Report*, OR/12/001.

[198] Nicot J P, Scanlon BR, 2012. Water use for shale-gas production in Texas, U.S. Environ. Sci. Technol. 2012, 46 (6), 3580−3586.

[199] Broderick et al, 2011.Shale gas: an updated assessment of environmental and climate change impacts. Tyndall Centre University of Manchester

[200] Chartered Institution of Water and Environmental Management, 2015. Written Submission to Environmental Audit Committee: Environmental Risks of Fracking Enquiry (FRA006), para 4

220. Several papers have noted that claims about employment generation associated with shale gas in the US have usually been over-stated,[201] [202] [203] and that initial economic booms often transform into long-term social and economic declines.[204] [205]

221. Six industry-sponsored reports (three of which had an academic affiliation) that highlighted the economic benefits of UNG were assessed by Kinnaman (2011).[206] He identified several shortcomings in the analyses including: a) assumptions that all the lease and royalty payments and the great majority of industry expenditure is spent locally; b) that the level of well activity is a function solely of the current gas price; c) erroneous interpretation of data; d) disregard of the impact on other users of the resource; and e) failure to assess whether the overall benefits of gas extraction exceed the costs. Kinnaman considered the consistent use of the term 'conservative estimates' in industry-sponsored reportage to be misleading and that estimates were more likely to be 'overstated'.

222. Lave and Lutz (2014) noted that where research on the social effects of UNG is available, it is not necessarily of adequate quality and that most of the economic analysis is speculative and not subject to academic peer-review.[207] The lack of funding for independent research has left a knowledge vacuum which has been largely filled by industry funded or produced literature. However, they also found that the limited research on the social and cultural impacts of UNG to be overwhelmingly negative. The authors also note that government agencies value ostensibly apolitical economic arguments so highly that they behave less like mediators in the debate and more as advocates for the industry.

223. Hughes (2013) also concluded that industry and government projections are 'wildly optimistic' and that shale gas and oil are neither cheap nor inexhaustible.[208] This analysis, based on data for 65,000 shale wells from an industry and government production database, showed

[201] Weber J, 2012. The effects of a natural gas boom on employment and income in Colorado, Texas, and Wyoming. *Energy Econ*. 34 (5), 1580–1588 (Sep). Doi: 10.1016/j.eneco.2011.11.013.

[202] Patridge M, Weinstein A, 2013. Economic implications of unconventional fossil fuel production. National Agricultural & Rural Development Policy Center. Available from: http://www.nardep.info/uploads/Brief15_EconomicsFossilFuel.pdf.

[203] Mauro F, Wood M, Mattingly M, Price M, Herzenberg S and Ward S, 2013. Exaggerating the Employment Impacts of Shale Drilling: How and Why. Multi-State Shale Research Collaborative. Available from https://pennbpc.org/sites/pennbpc.org/files/MSSRC-Employment-Impact-11-21-2013.pdf

[204] Jacquet J, 2009. Energy Boomtowns & Natural Gas: Implications for Marcellus Shale Local Governments & Rural Communities. NERCRD Rural Development Paper N° 43. Available from: http://aese.psu.edu/nercrd/publications/rdp/rdp43.

[205] Christopherson S, Rightor N, 2011. How should we think about the economic consequences of shale gas drilling? A Comprehensive Economic Impact Analysis of Natural Gas Extraction in the Marcellus Shale. Working Paper, City and Regional Planning, Cornell University. Available from: http://cce.cornell.edu/EnergyClimateChange/NaturalGasDev/Documents/PDFs/Comprehensive%20Economic%20Analysis%20project.pdf.

[206] Kinnaman T, 2011. The economic impact of shale gas extraction: A review of existing studies. Ecological Economics 70 (2011) 1243–1249

[207] Lave and Lutz, 2014. Hydraulic Fracturing: A Critical Physical Geography Review. Geography Compass 8/10 (2014): 739–754, 10.1111/gec3.12162

[208] Hughes DJ, 2013. A reality check on the shale revolution. Nature 494, 307–308

well and field productivity declining rapidly, production costs in many cases exceeding current gas prices, and production requiring increased drilling and major capital input to maintain production. He identifies a familiar pattern of an initial drilling boom, exploitation of 'sweet spots' (small, highly productive areas) followed by the drilling of more marginal areas, and then rapid decline within a few years. The investment required for new wells to maintain supply often exceeds sales income, which in turn necessitates higher gas prices.

224. Concerns about boom-bust cycles were also described by Haefele and Morton (2009) in their assessment of the large increase in natural gas wells in the Rocky Mountain region from 1998-2008. A review of specific case studies which highlighted the spectre of a subsequent local economy 'bust' precipitated by a drop in natural gas prices.[209]

225. Paredes et al (2015) used two econometric methods to isolate and quantify the effect of UNG on local income and employment.[210] They found that the direct income effects of Marcellus shale UNG development had a negligible income impact on the general population. While local employment effects were more substantial, many of the new jobs were low paid and taken up by outsiders who would tend to spend/send much of their income home.

226. Sovacool (2014) described the economic benefits of a number of shale booms. These included about 29,000 new jobs and $238m in tax revenues in Pennsylvania in 2008; a contribution of $4.8 billion to gross regional product, 57,000 new jobs and $1.7 billion in tax revenue across West Virginia and Pennsylvania in 2009; and $11.1 billion in annual output representing 8.1% of the region's economy and 100,000 jobs in the Barnett Shale in Texas in 2011.[211] However, the review also identified the complexities of assessing economic impact and the expense of cost overruns, accidents and leakages, and concluded that the benefits of SGP are uncertain and conditional on the "right" mix of technological systems; operating procedures, government regulations, and corporate values at each locality.

227. Wren et al (2015) noted that variation in the literature highlighted the challenge of capturing accurate data on workers' place of residence and that increases in employment may have little benefit to those localities directly faced with the costs of UNG activity. Their analysis of local employment in Pennsylvania found that while UNG activity had had a positive effect on employment, it was only statistically significant for counties in which 90 or more wells were drilled in a given year. Hardy and Kelsey (2014) found modest employment increases in counties with drilling activity in Marcellus shale development in Pennsylvania, and that many of the new jobs were going to non-residents, leaving minimal employment impact on residents.[212]

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[209] Haefele, M. and P. Morton. 2009. The influence of the pace and scale of energy development on communities: Lessons from the natural gas drilling boom in the Rocky Mountains. *Western Economics Forum* 8(2): 1-13.

[210] Paredes et al 2013. Income and employment effects of shale gas extraction windfalls: Evidence from the Marcellus region. Energy Economics 47 (2015) 112–120

[211] Sovacool 2014. Cornucopia orcurse?Reviewingthecostsandbenefits ofshale gas hydraulicfracturing(fracking) RenewableandSustainableEnergyReviews37(2014)249–264

[212] Hardy and Kelsey 2014. LOCAL AND NON-LOCAL EMPLOYMENT ASSOCIATED WITH MARCELLUS SHALE DEVELOPMENT IN PENNSYLVANIA

228. Munasib and Rickman (2014) considered that while unconventional shale oil and gas exploration increased energy sector employment, the impacts on other parts of local economies were poorly understood.[213] They examined the broader regional economic effects of the industry in three shale plays in Arkansas, North Dakota and Pennsylvania including total employment, wage and salary employment, per capita income, the poverty rate, population, and employment in accommodation and food services, construction and retail sectors. A synthetic control method was used to predict economic activity occurring in the absence of increased unconventional energy development. They found significant positive effects for oil and gas counties in North Dakota across all regional labour market metrics. However, they also found that positive effects in Arkansas were only identified in counties with the most intensive shale gas production. They considered that the positive impacts of the employment effects on the local economy were smaller than those estimated in other analyses and that local inflation and other adverse effects had a negative impact on the local quality of life. In addition, they found no significant positive effects in Pennsylvania. The study cautions against overestimating the potential of the industry to revive local economies and highlights that areas with significant levels of economic activity such as agriculture and tourism, may be more likely to experience adverse economic effects.

229. Weber JG (2012) had also previously estimated modest increases in employment and income associated with increased UNG in counties in Colorado, Texas and Wyoming.[214] Analysis of gas deposit and production data with economic data for 1998/99 to 2007/08 suggested the creation of fewer than 2.5 jobs per million dollars of gas production; an annual employment increase of 1.5% on pre-boom levels.

230. Rural North Dakota experienced an oil and UNG boom in the 2010s which was estimated to have contributed over a billion dollars to the State's finances and created 65,000 new jobs. This region had seen previous oil related booms in the 1950s and late 1970s which had led to housing shortages, more expensive public services, and a legacy of costs for obsolete infrastructure. Weber et al (2014) assessed the benefits of this five-year boom, the associated social challenges and potential solutions, through interviews with social workers and Directors of Social Care.[215] They noted housing as a recurrent theme, especially inadequate supply and high housing costs. Social Services Directors also reported an increase in child protection issues, increasing day care shortage and a diminishing supply of foster homes. Data from the police suggested 'troubling increases in domestic violence issues disproportionate to population'. Benefits were also raised and included economic development, partnerships with the industry, and decreases in benefit support. However, these were regarded as 'mixed blessings'. The authors advised that their findings should be treated with caution due to the limitations of a small cross-sectional study.

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[213] Munasib and Rickman, 2014 Regional Economic Impacts of the Shale Gas and Tight Oil Boom: A Synthetic Control Analysis

[214] Weber J, 2012. The effects of a natural gas boom on employment and income in Colorado, Texas, and Wyoming. Energy Economics 34 (2012) 1580–1588

[215] Weber et al, 2014. Shale gas development and housing values over a decade: Evidence from the Barnett Shale.

231. Muehlenbachs et al (2015) used a methodology to quantify the real or perceived effects of shale gas development on property prices in Pennsylvania.[216] They had access to a substantial property sales dataset and used both a technique to control for potential confounders. They found that the prices of homes dependent on groundwater are negatively affected by proximity to shale gas developments (up to -16.5% for those within 1 km), while the value of homes on a mains supply showed a small increase. However, the latter was only applicable to homes proximal to *producing* wells which received homeowner royalty payments, and if the wells are not visible from the property.

232. Jones et al (2014) reviewed the potential implications for UK property and investment in a professional briefing note based on internet resources, peer reviewed papers and government agency research.[217] They noted reasons for concern about adequate and affordable insurance cover and problems with obtaining mortgages for homes in close proximity to shale gas operations. In England, a leading firm of surveyors noted that house prices could fall by as much as 30%.

233. Barth (2013) noted that UNG activities could cause increased demand and costs for rental properties as well as a reduction in house prices, difficulties in obtaining property insurance and a negative impact on future construction and economic development.[218] While Barth recognised that shale gas will generate some local and regional jobs and revenues, the levels of both have probably been exaggerated in the industry-funded literature. He notes that some studies have used inappropriate economic modelling assumptions such as using costs from Texas which has a long established extractive industry infrastructure and applying them to areas without infrastructure. In addition, costs from such areas like Texas which is predominantly non-urban with smaller populations and with lower economic diversity would be different from areas dependent on agriculture, tourism, organic farming, hunting, fishing, outdoor recreation, and wine and brewing.

234. Large-scale UNG imposes costs on local social, health and emergency services as well as the environmental costs such as traffic congestion and road damage. Abramzon et al (2014) estimated that Marcellus UNG-related heavy truck traffic caused between $13-23,000 of damage per well to state maintained roads in 2011.[219]

235. Haefele and Morton (2009) concluded that the same natural gas industry 'boom' that brings some benefits for rural communities also brings an influx of non-local workers; increased crime, housing costs and demand for public services; and additional burdens on local infrastructure.

[216] MuehlenbachsL, Spiller E and Timmins C, 2015. The Housing Market Impacts of Shale Gas Development *American Economic Review 2015, 105(12): 3633–3659*
[217] Jones P, Comfort D and Hillier D, 2014. Fracking for shale gas in the UK: property and investment issues'. Journal of Property Investment & Finance, 32,5: 505–517
[218] Barth J, 2013. THE ECONOMIC IMPACT OF SHALE GAS DEVELOPMENT ON STATE AND LOCAL ECONOMIES: BENEFITS, COSTS, AND UNCERTAINTIES**.** NEW SOLUTIONS, Vol. 23(1) 85-101, 2013
[219] Abramzon et al 2014 Estimating The Consumptive Use Costs of Shale Natural Gas Extraction on Pennsylvania Roadways. Journal of Infrastructure Systems10.1061/(ASCE)IS.1943-555X.0000203, 06014001.

236. Following a study[220] that reported a decline in cow numbers and milk production in drilled areas, Finkel et al (2013) compared the effect of UNG activities on milk production in five Pennsylvania counties with the most unconventional drilling activity were six neighbouring counties with much fewer wells.[221] They found that the number of cows and total volume of milk production declined more in the most fracked counties compared to the six comparison counties. The authors recognised the weaknesses of their study but recommended further research given the importance of the milk production industry in Pennsylvania.

237. The literature on green energy strongly suggests that households are willing to pay (WTP) a premium for electricity from green energy sources such as wind, solar, and biomass (Borchers et al., 2007; Roe et al., 2001 and Susaeta et al., 2011) (Gerpott and Ilaha, 2010, Oliver et al., 2011 and Scarpa and Willis, 2010).

238. Popkin et al (2013) explored the likely welfare impacts of using UNG extracted by hydraulic fracturing for household electricity in an economic choice experiment involving 515 households from nine New York counties within the Marcellus Shale region and 18 outside the shale region.[222] The analysis controlled for age, gender, education, place of residence and proximity to UNG sites. They found respondents being willing to accept UNG derived electricity provided their monthly bills were reduced by between $22-$48 (mean bill $124) with the required discounting increasing with increased proximity to UNG sites. Respondents also generally expressed a preference to continue with the status quo (out of state fossil fuel and nuclear energy).

239. This negative local perception of UNG is also reflected in Bernstein et al's (2013) contingent valuation study of a random sample of Susquehanna Valley Pennsylvania residents' (n=186) WTP for eliminating the risks of water pollution due to hydraulic fracking.[223] This found that residents were willing to pay up to $10.50 a month for additional safety measures to protect local watersheds from shale gas extraction.

240. A comprehensive assessment of the economic effects of shale gas development involves looking at who will benefit from the economic benefits and new jobs; who will suffer the costs associated with shale gas development, and who will pay for the different costs associated with shale gas production. The latter includes the tax payer who has to foot the bill for a large amount of the required infrastructure and the necessary levels of effective regulation.

241. Government policy is also important. In the UK, the government has supported recommendations to provide local communities £100,000 per well site where hydraulic fracturing

[220] Adams and T. W. Kelsey, *Pennsylvania Dairy Farms and Marcellus Shale, 2007-2010*, 2012, Penn State Cooperative Extension, College of Agricultural Sciences; Marcellus Education Fact Sheet, http://pubs.cas.psu.edu/freepubs/pdfs/ ee0020.pdf (accessed June 15, 2012)

[221] Finkel et al, 2013. MARCELLUS SHALE DRILLING'S IMPACT ON THE DAIRY INDUSTRY IN PENNSYLVANIA: A DESCRIPTIVE REPORT. NEW SOLUTIONS, Vol. 23(1) 189-201, 2013

[222] Popkin et al, 2013. Social costs from proximity to hydraulic fracturing in New York State. Energy Policy62(2013)62–69

[223] Bernstein, P., Kinnaman, T. C., & Wu, M. (2013). Estimating willingness to pay for river amenities and safety measures associated with shale gas extraction. *Eastern Economic Journal*, 39(1), 28-44.

takes place at the exploration or appraisal stage. In addition, local communities can expect a share of proceeds from the production stage of 1% of revenues. In January 2014 the Prime Minister suggested that this could be worth £5-10 m for a production site over its lifetime. Local councils have also been incentivised to encourage shale gas production by being allowed to keep 100% of business rates they collect from shale gas sites (double the current 50% figure).

Fugitive emissions

242. Fugitive emissions are gases (mainly methane, but also other hydrocarbons such as ethane) that are unintentionally lost to the atmosphere during the process of gas extraction, collection, processing and transportation. They can emanate from above or below the ground. [Pressure relief valves are also designed to purposefully vent gas.]

243. Above the ground, leaks may arise from any of the 55 to 150 connections between pieces of equipment such as pipes, heaters, meters, dehydrators, compressors and vapour-recovery apparatus of a typical well.[224] Leaks and emissions also occur in the distribution system used to supply gas to end consumers. Large emissions of VOCs have been observed on oil and gas (O&G) well pads because of leaks from dehydrators, storage tanks, compressor stations, and pneumatic devices and pumps, as well as evaporation and flow back pond water.[225]

244. Key emission sources in the gas production process are from well completions and liquids unloading. Methane is released during well completion as fracking fluid returns to the surface prior to gas flowing at a high production rate.

245. Methane emission rates will vary from one area to another because gas reservoirs vary by age, geologic properties, ease of maintenance (accessibility), and local practice. For example, intermittent activities that can result in high short-term emissions, such as well completions and liquid unloadings may be more common in one area compared to another.[226]

246. Current understanding of the distribution of emissions across the global well population is extremely poor within the literature and further research is required to detail and quantify the factors affecting unloading emissions such as well age, reservoir properties, equipment used and operational strategies.[227]

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[224] Howarth and Ingraffea 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change (2011) 106:679–690

[225] Warneke C, Geiger F, Edwards PM, Dube W, Petron G, et al, 2014. Volatile organic compound emissions from the oil and natural gas industry in the Uintah Basin, Utah: oil and gas well pad emissions compared to ambient air composition. Atmos. Chem. Phys. 14, 10977e10988. http://dx.doi.org/10.5194/acp-14-10977-2014.

[226] Zavala-Aaraiza et al (2015) Reconciling divergent estimates of oil and gas methane emissions PNAS | December 22, 2015 | vol. 112 | no. 51 | 15597–15602

[227] Balcombe, Anderson, Speirs, Brandon and Hawkes, 2015. Methane and CO2 emissions from the natural gas supply chain. London: Sustainable Gas Institute

247. Estimates of emissions from liquids unloading are highly variable. Whilst this may be high for some wells, many wells do not vent at all during unloading.[228]

248. According to a report produced by the Sustainable Gas Institute (SGI), there is still an incomplete and unrepresentative data set for a number of key emission sources. Specifically, more data are required for liquids unloading, well completions with RECs and transmission and distribution pipelines.[229] SGI also note a lack of transparency in data and accounting for methane emissions across all of the LNG stages.

249. Fugitive emissions are a major health hazard because methane is a potent greenhouse gas (GHG). If the amount of fugitive emissions exceeds a certain threshold, the argument that shale gas is a 'clean energy source' relative to coal or oil falls apart. Accurate measures of fugitive emissions produced by the O&G industry are therefore important.

250. Methods to quantify fugitive emissions are typically divided into two groups: bottom up methods and top down methods.

251. Bottom up methods use direct measurements of leakage rates from empirical studies to calculate emission factors (EFs) for different sources of leakage. These EFs are then applied to the number of such sources (and their activity levels) to create an inventory of emissions from which a total emission estimate is calculated. In other words, inventories quantify emissions on the basis of assumptions about leakage frequency and rates across the different parts of the shale gas system, and reports about activity levels.

252. This is the basis for the EPA's Inventory of Greenhouse Gas Emissions and Sinks which provides an overall national emission estimate by sector for the US. The EPA also has a Greenhouse Gas Reporting Program (GHGRP) which involves mandatory reporting by O&G operators of GHGs from all sources that emit greater than 25 000t of CO_2e per year.

253. In the US, attempts to establish accurate emissions inventories have been hindered by data gaps, a reliance of self-reported data collection, and the use of outmoded emissions factors.[230] Macey et al (2014) also note how the direct measurement of air pollutants from onshore gas operations has been limited by inadequate access to well pads and other infrastructure; the unavailability of a power source for monitoring equipment; and unscheduled episodes of flaring, fugitive releases and movements of truck traffic.[231]

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[228] Balcombe, Anderson, Speirs, Brandon and Hawkes, 2015. Methane and CO2 emissions from the natural gas supply chain. London: Sustainable Gas Institute
[229] Balcombe, Anderson, Speirs, Brandon and Hawkes, 2015. Methane and CO2 emissions from the natural gas supply chain. London: Sustainable Gas Institute
[230] Field RA, Soltis J, Murphy S: Air quality concerns of unconventional oil and natural gas production. Environ Sci Process Impacts 2014, 16:954–969.
[231] Macey et al, 2014. Air concentrations of volatile compounds near oil and gas production: a community-based exploratory study. Environmental Health 2014, 13:82 doi:10.1186/1476-069X-13-82

254. Bottom-up studies vary in terms of distance to site, sample frequency, and chemicals targeted which helps explain the range of findings in the published literature.

255. Top down methods measure methane concentrations directly in the atmosphere, usually downwind from a source or group of sources, as a basis for estimating the emission levels of a given source area. Models are then used to apportion a percentage of the total emissions to different sources of methane in the given source area.

256. Bottom-up estimations of fugitive emissions used in the official US inventories are generally accepted as being prone to underestimation. Independent top-down investigations suggest that GHGRP estimates may underestimate the real emission rate by up to a factor of 3.8.[232]

257. The reasons for this include the use of outdated EFs (most of the 80 different EPA EFs associated with O&G operations are based on a study done in the 1990s[233]); inadequate sampling and the failure to account for 'super-emitters' (methane emissions from individual wells and gas processing facilities do not exhibit a normal distribution, but tend to display a skewed distribution with a 'fat-tail' of 'super-emitters[234]); assumptions that operators are applying best practice; inaccurate counts and location of sites, facilities, and equipment under or non-reporting by O&G operators;[235] and the assumption that EFs are consistent across the industry and different regions.[236] [237]

258. Brandt et al's review of 20 years of technical literature on natural gas emissions in the US and Canada found that official inventories consistently underestimate actual CH_4 emissions.[238] According to Brandt et al, because measurements for generating EFs are expensive, sample sizes are usually small and affected by sampling bias due to reliance upon self-selected cooperating facilities. In addition, because emissions distributions have 'fat tails', small sample sizes are likely to underrepresent high-consequence emissions sources.

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[232] Lavoie 2015 *Aircraft-Based Measurements of Point Source Methane Emissions in the Barnett Shale Basin*, Lavoie et al., Environmental Science and Technology, vol.49 no.13 pp.7904-7913, http://pubs.acs.org/doi/pdf/10.1021/acs.est.5b00410

[233] Karion et al, 2013 *Methane emissions estimate from airborne measurements over a western United States natural gas field*, Geophysical Research Letters, vol.40 no.16, http://onlinelibrary.wiley.com/doi/10.1002/grl.50811/pdf

[234] Fat-tail sites do not necessarily have persistently high emissions but may represent short-term emission events caused by maintenance activities or malfunctions.

[235] Lavoie 2015 *Aircraft-Based Measurements of Point Source Methane Emissions in the Barnett Shale Basin*, Lavoie et al., Environmental Science and Technology, vol.49 no.13 pp.7904-7913, http://pubs.acs.org/doi/pdf/10.1021/acs.est.5b00410

[236] Karion et al, 2013 *Methane emissions estimate from airborne measurements over a western United States natural gas field*, Geophysical Research Letters, vol.40 no.16, http://onlinelibrary.wiley.com/doi/10.1002/grl.50811/pdf

[237] Zavala-Aaraiza et al (2015) Reconciling divergent estimates of oil and gas methane emissions PNAS | December 22, 2015 | vol. 112 | no. 51 | 15597–15602

[238] Brandt et al, 2014. *Methane Leaks from North American Natural Gas Systems*, Science, vol.343 pp.733-735, http://psb.vermont.gov/sites/psb/files/CLF-SC-2%20Science-Methane%20Leaks.pdf

259. The methodological challenges in accounting for fugitive emissions are demonstrated by large year-to-year revisions of the reported emissions by the EPA.[239] For example, the estimated national average production-sector leak rate for 2008 increased from approximately 0.16% (of total gas produced) in its 2010 report, to 1.42% in the 2011 and 2012 reports, before being revised down to 0.88% in the 2013 report.[240] These changes led the EPA's Office of Inspector General to call for improved emissions data for the natural gas production sector.[241]

260. According to Howarth and Ingraffea, 1.9% of the total production of gas from an unconventional shale-gas well is emitted as methane during well completion [made up of losses from flowback fluids (1.6%) and drill out (0.33%)].[242] Additional fugitive emissions (0.3 – 3.5%) continue at the well site after well completion (from leakage at connections, pressure relief valves, pneumatic pumps, dehydrators and gas processing equipment), while emissions during transport, storage and distribution are estimated to be an additional 1.4% to 3.6%.

261. Altogether, Howarth and Ingraffea estimate that 3.6% to 7.9% of methane from shale-gas production escapes to the atmosphere. They estimate that emissions are *at least* 30% and possibly twice as great as those from conventional gas due to the extra emissions that arise from hydraulic fracturing (as methane escapes from flowback fluids) and during drill out after fracturing.

262. Caulton et al's assessment of the literature on estimates of methane emissions from unconventional gas production since 2010 is that emission rates range from 0.6 to 7.7% at the well site and during processing over the lifetime production of a well; and from 0.07 to 10% during transmission, storage and distribution to consumers. The highest published estimates for combined methane emissions (2.3–11.7%) are based on actual top-down measurements in specific regions.[243] [244]

263. Petron et al's (2014) top down measurement of methane emissions in the Denver-Julesburg Basin in northeastern Colorado over 2 days in May 2012 was used to estimate the emissions from oil and natural gas operations by subtracting the estimated contribution of other sources of

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[239] Karion et al, 2013 *Methane emissions estimate from airborne measurements over a western United States natural gas field*, Geophysical Research Letters, vol.40 no.16, http://onlinelibrary.wiley.com/doi/10.1002/grl.50811/pdf

[240] These changes were caused by different EFs for calculating emissions from liquid unloading, unconventional completions with hydraulic fracturing, and the refracturing of natural gas wells. The main driver for the 2013 reduction was a report prepared by the oil and gas industry, which contended that the estimated emissions from liquid unloading and refracturing of wells in tight sands or shale formations should be lower.

[241] U.S. Environmental Protection Agency Office of Inspector General (2013), EPA Needs to Improve Air Emissions Data for the Oil and Natural Gas Production Sector, EPA OIG, Washington, D. C.

[242] Howarth and Ingraffea, 2011. *Methane And The Greenhouse-Gas Footprint Of Natural Gas From Shale Formations – A Letter*, Climatic Change, vol.106 no.4 pp.679-690. http://link.springer.com/content/pdf/10.1007%2Fs10584-011-0061-5.pdf

[243] Pétron G, et al. (2012) Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. J Geophys Res, 10.1029/2011JD016360.

[244] Karion A, et al. (2013) Methane emissions estimate from airborne measurements over a western United States natural gas field. Geophys Res Lett, 10.1002/grl.50811.

methane (livestock farming, landfills, wastewater treatment and natural micro-seepage).[245] The estimated contribution from O&G operations was on average 19.3 ± 6.9 t/h, 75% of the total top down measure. The measurement was almost 3 times higher than an hourly emission estimate based on the EPA's GHGRP. The level of fugitive emissions as a fraction of total gas production was 4.1 ± 1.5%; similar to findings reported from a study in 2008 of the same region.[246]

264. Peischl et al's study of methane, carbon dioxide, carbon monoxide and C2–C5 alkane levels across the Los Angeles basin in 2010, found that methane emissions were greater than that which would be expected from bottom-up state inventories. More than half the emissions came from fugitive losses from pipelines and urban distribution systems and geologic seeps.[247]

265. Karion et al's (2013) study of atmospheric measurements of CH_4 from a natural gas and oil production field in Utah in 2012 found an emission rate that corresponded to 6.2% - 11.7% of average hourly natural gas production.[248] The findings were consistent with results from previous top-down studies which have found inventory estimates to be too low.

266. Another top-down measurement of methane over several regions (representing over half of US shale gas production), found emission rates varying from one region to the next, and being generally lower than those reported in earlier studies.[249] Methane emissions as a percentage of total volume of natural gas extracted was 1.0–2.1% in the Haynesville region, 1.0–2.8% in the Fayetteville region, and 0.18–0.41% in the Marcellus region in northeastern Pennsylvania. The relatively low fugitive emission rates found in the study are thought to be due in part to the composition of the fossil fuel extracted and the use of more efficient technology. It should be noted that the figures reported here do not include an estimate of fugitive losses during the transmission and from end-use stages of the gas production system. The authors note that repeated measurements would be necessary to determine the extent to which their one day measures of CH_4 are representative of emission rates over the full life cycle of fossil fuel production, and why twenty-fold differences in loss rates have been reported in the literature for different oil and gas-producing regions.

267. Karion et al's (2015) estimates of regional methane emissions from O&G operations (including production, processing and distribution) in the Barnett Shale (Texas), using airborne

[245] Pétron et al 2014 *A new look at methane and nonmethane hydrocarbon emissions from oil and natural gas operations in the Colorado Denver-Julesburg Basin*, Journal of Geophysical Research: Atmospheres, vol.119 no.11 pp.6836-6852, http://onlinelibrary.wiley.com/doi/10.1002/2013JD021272/pdf

[246] Pétron et al 2012 *Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study*, Journal Of Geophysical Research, vol.117 no.D4, http://www.fraw.org.uk/library/extreme/petron_2012.pdf

[247] Peischl et al 2013. *Quantifying sources of methane using light alkanes in the Los Angeles basin, California*, Journal of Geophysical Research: Atmospheres, vol.118 no.10 pp.4974-4990, 27th http://www.fraw.org.uk/library/extreme/peischl_2013.pdf

[248] Karion A, et al. (2013) Methane emissions estimate from airborne measurements over a western United States natural gas field. Geophys Res Lett, 10.1002/grl.50811.

[249] Peischl et al, 2015. *Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions*, Journal of Geophysical Research: Atmospheres, vol.120 pp.2119-2139, http://onlinelibrary.wiley.com/doi/10.1002/2014JD022697/pdf7

atmospheric measurements, found measures that agreed with the EPA estimate for nationwide CH_4 emissions from the natural gas sector, but higher than those reported by the EDGAR inventory or the EPA's GHGRP.[250] The emissions rate amounted to 1.3−1.9% of total CH_4 production which is lower than rates ranging from 4 to 17% found in other studies.[251] [252] [253]

268. Lan et al (2015) quantified fugitive CH_4 emissions from more than 152 facilities, including wellpads, compressor stations, gas processing plants and landfills from ONG operations in the Barnett Shale.[254] They estimated a total wellpad emission rate of 1.5 × 105 kg/h in the area, with rates between individual wellpads ranging from 0.009 to 58 kg/h and being linearly correlated with gas production. Methane emissions from compressor stations and gas processing plants were substantially higher, with some "super emitters" having emission rates of 3447 kg/h, more then 36,000-fold higher than reported by the EPA's GHGRP. The emission rate as a proportion of total gas production varied from 0.01% to 47.8% with a median and average value of 2.1% and 7.9%, respectively.

269. Measurements of methane emissions by Lavoie et al (2015) at eight different high-emitting point sources in October 2013 in the Barnett Shale, Texas (four gas processing plants, one compressor station and three landfills) were compared to other aircraft- and surface-based measurements of the same facilities, and to estimates reported to the EPA's GHGRP.[255] For the eight sources, CH_4 emission measurements were a factor of 3.2−5.8 greater than the GHGRP-based estimates. Summed emissions totalled 7022 ± 2000 kg hr−1, roughly 9% of the entire basin-wide CH_4 emissions estimated from regional mass balance flights during the campaign.

270. Allen et al's (2013) study which consisted of direct measurements of methane emissions at 190 onshore natural gas sites in the US (150 production sites, 27 well completion flowbacks, 9 well unloadings, and 4 workovers) also found emissions measurements that varied by orders of magnitude.[256] However, their overall estimate of emissions for completion flowbacks, pneumatics, and equipment leaks amounted to 0.42% of gross gas production which is

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[250] Karion et al, 2015. *Aircraft-Based Estimate of Total Methane Emissions from the Barnett Shale Region*, Environmental Science and Technology, vol.49 no.13 pp.8124-8131. http://pubs.acs.org/doi/pdf/10.1021/acs.est.5b00217

[251] Karion et al 2013. Methane emissions estimate from airborne measurements over a western United States natural gas field. Geophys. Res. Lett. 40 (16), 4393−4397

[252] Peischl, J; et al. Quantifying sources of methane using light alkanes in the Los Angeles basin, California. J. Geophys. Res.: Atmos. 2013, 118 (10), 4974−4990.

[253] Wennberg, P. O et al. On the sources of methane to the Los Angeles atmosphere. Environ. Sci. Technol. 2012, 46 (17), 9282−9289.

[254] Lan et al, 2015 *Characterizing Fugitive Methane Emissions in the Barnett Shale Area Using a Mobile Laboratory*, Environmental Science and Technology, vol.49 no.13 pp.8139-8146, https://www.researchgate.net/profile/Robert_Talbot/publication/279863703_Characterizing_Fugitive_Methane_Emissions_in_the_Barnett_Shale_Area_Using_a_Mobile_Laboratory/links/55a3bfdb08aee1d98de0f78d.pdf

[255] Lavoie et al 2015 *Aircraft-Based Measurements of Point Source Methane Emissions in the Barnett Shale Basin*, Environmental Science and Technology, vol.49 no.13 pp.7904-7913, http://pubs.acs.org/doi/pdf/10.1021/acs.est.5b00410

[256] Allen DT, et al. (2013) Measurements of methane emissions at natural gas production sites in the United States. Proc Natl Acad Sci USA 110(44):17768–17773.

considerably lower than other findings from other studies and even lower than the EPA's inventory-based rates. However, two papers published in 2015 have indicated that the data in the Allen et al's paper may have been flawed.[257]

271. Zavala-Aaraiza et al's (2015) study constructed a customised bottom-up CH_4 inventory in the barnett region that was based on extensive local measurements of facility-wide emissions from production sites, compressor stations, and processing plants; updated facility counts; and an explicit account of the contribution of high-emitters (the estimated emission distributions imply that, at any one time, 2% of facilities are responsible for half the emissions).[258] High-emitters were divided roughly equally among production sites, compressors, and processing plants. They estimated that CH_4 emissions for the Barnett region to be 59 Mg CH4/h (48–73 Mg CH4/h; 95% CI), with the three main sources being production sites (53%), compressor stations (31%), and processing plants (13%). This equates to a loss of 1.5% (1.2–1.9%) of total Barnett production. Their measure of emissions was 1.9 times the estimated emissions based on the EPA's Greenhouse Gas Inventory and 3.5 times that of the GHGRP.

272. The leakage rate is low enough for gas-fired electricity *in this region* to be less climate forcing than coal-fired electricity. However, long-distance transmission and storage of natural gas results in a substantial increment of CH_4 emissions that would need to be considered when analysing the climate implications of natural gas consumption in regions that are not proximate to a production area.[259]

273. Zavala-Aaraiza et al note that more work is needed to understand the characteristics that cause an individual site to be a high-emitter.[260] They also note that the challenge facing operators is that high-emitters are always present (at the basin scale) but occur at only a subset of sites at any one time, and move from place to place over time.

274. Lyon et al (2016) used a spatially resolved emission inventory, to measure methane emissions from the O&G industry and other sources in the Barnett Shale region in October 2013.[261] They were estimated to be 72,300 (63,400−82,400) kg/hr of which 46,200 (40,000−54,100) kg/hr were O&G emissions (64% of the total). About 19% of emissions came from fat-tail sites representing less than 2% of all sites. The measured estimate was higher than

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[257] See: a) Howard T, Ferrarab TW, Townsend-Small A. Sensor transition failure in the high flow sampler: implications for methane emission inventories of natural gas infrastructure. *J Air Waste Manag Assoc*. 2015;65: 856–862; and b) 39. Howard T. University of Texas study underestimates national methane emissions inventory at natural gas production sites due to instrument sensor failure. *Energy Sci Eng*. 2015; DOI:10.1002/ese3.81.

[258] Zavala-Aaraiza et al (2015) Reconciling divergent estimates of oil and gas methane emissions PNAS | December 22, 2015 | vol. 112 | no. 51 | 15597–15602

[259] Zavala-Aaraiza et al (2015) Reconciling divergent estimates of oil and gas methane emissions PNAS | December 22, 2015 | vol. 112 | no. 51 | 15597–15602

[260] Zavala-Aaraiza et al (2015) Reconciling divergent estimates of oil and gas methane emissions PNAS | December 22, 2015 | vol. 112 | no. 51 | 15597–15602

[261] Lyon et al, 2015. *Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region*, Environmental Science and Technology, vol.49 no.13 pp.8147-8157, http://pubs.acs.org/doi/pdf/10.1021/es506359c

the EPA Greenhouse Gas Inventory, the EPA's GHGRP, and the Emissions Database for Global Atmospheric Research (EDGAR) by factors of 1.5, 2.7, and 4.3, respectively. Their estimated emission rate was equivalent to 1.2% (1.0−1.4%) of gas production.

275. A study published by Schneising et al (2014) assessed global and regional trends in atmospheric methane between 2003 and 2012 and found that methane concentrations had risen dramatically in the northern hemisphere.[262] By evaluating trends in drilling and hydraulic fracturing activity in two large shale regions in the US (the Eagle Ford in Texas and the Bakken in North Dakota), the authors estimated methane emission rates of 9.5% (±7%) in terms of energy content during the 2009–2011 period.

276. Fugitive emissions from abandoned wells have also become a growing concern. In a study which involved direct measurements of methane fluxes from abandoned O&G wells in Pennsylvania, much higher methane flow rates were found when compared to control locations.[263] Three out of 19 measured wells were high emitters that had methane flow rates three orders of magnitude larger than the median flow rate. Given that there are millions of abandoned wells across the US, this may mean that there are tens or hundreds of thousands of high emitting wells. The authors recommend that measurements of methane emissions from abandoned wells be included in greenhouse gas inventories.

277. A study of fugitive emissions of methane from former onshore (conventional) O&G exploration and production in the UK selected 66% (n= 102) of all wells which appeared to have been decommissioned (abandoned) from 4 different basins and analysed the soil gas above each well relative to a nearby control site of similar land use and soil type.[264] Of these wells, 30% had CH4 levels at the soil surface that was significantly greater than their respective control. Conversely, 39% of well sites had significantly lower surface soil gas CH4 concentrations than their respective control. The authors interpret the elevated soil gas CH4 concentrations to be the result of well integrity failure, but do not know the source of the gas nor the route to the surface. The data suggest a mean fugitive emission of 364 ± 677 kg CO2eq/well/year. But the authors note that all the study sites had been decommissioned in line with current best practice recommendations and that onshore wells which have not been appropriately decommissioned are likely to emit greater levels of methane. Furthermore, this study did not assess the potential for diffuse leakage into the surrounding groundwater and enhanced release over a broad area.

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[262] Schneising O, Burrows JP, Dickerson RR, Buchwitz M, Reuters M, Bovensmann H. Remote sensing of fugitive emissions from oil and gas production in North American tight geological formations. Earths Future, 2014;2: 548–558

[263] Kang et al, 2014 *Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania.* ,PNAS, vol.111 no. 51 pp.18173-18177, http://www.pnas.org/content/111/51/18173.full.pdf?with-ds=yes

[264] Boothroyd et al 2016 *Fugitive emissions of methane from abandoned, decommissioned oil and gas wells*, Science of The Total Environment, vol.547 pp.461-469, http://www.sciencedirect.com/science/article/pii/S0048969715312535/pdfft?md5=28d125f6f39d20a2e7783d9dd6443062& pid=1-s2.0-S0048969715312535-main.pdf

278. In general, methane emissions in the US have been under-estimated. One recent quantitative estimate of the spatial distribution of anthropogenic methane sources showed that EPA inventories and the Emissions Database for Global Atmospheric Research (EDGAR) have underestimated methane emissions by a factor of ~1.5 and ~1.7, respectively.[265] The discrepancy in estimates were particularly pronounced in south-central US where fossil fuel extraction and refining are prominent.[266] According to this paper, regional methane emissions due to fossil fuel extraction and processing could be 4.9 ± 2.6 times larger than in EDGAR.

279. The observed increase in atmospheric methane concentrations over the US parallels global trends. The global burden of atmospheric methane rose by 1–2% in the 1970s and 1980s, stabilized in the 1990s, but has been rising again since the mid-2000s.[267] [268]

280. The increase of US methane emissions by more than 30% over the past decade is a major contribution to this trend. According to Turner et al (2016), US anthropogenic methane emissions could account for up to 30–60% of the global increase.[269]Caulton et al also agree that increase in anthropogenic CH_4 emission in the US, caused primarily by natural gas systems and enteric fermentation, play a significant part in these global trends.[270]

281. The 20% increase in O&G production (including a nine fold increase in shale gas production) from 2002 to 2014 is a likely cause for the rise in methane emissions seen in the US, although a better understanding of US anthropogenic methane emissions, particularly those from the livestock and O&G sectors, is needed before any definitive conclusions can be made.

282. Atmospheric methane mostly arises from three sources: biogenic methane produced by microbes from organic matter under anaerobic conditions (e.g. in wetlands, ruminants, and waste deposits), thermogenic methane formed in geological processes and released by oil and gas production, and pyrogenic methane produced by incomplete combustion processes such as in biomass burning. The rise in methane concentrations at the global level is believed to be driven by a combination of increased biogenic methane emissions from the tropical wetlands and growing oil and natural gas production. The contribution made by oil and gas operations to

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[265] Miller 2013 *Anthropogenic emissions of methane in the United States*, PNAS, vol.110 no.50 pp.20018-20022, 10th December 2013 http://www.pnas.org/content/110/50/20018.full.pdf?with-ds=yes

[266] Emissions due to ruminants and manure are were also up to twice the magnitude of existing inventories.

[267] Turner et al, 2016. *A large increase in U.S. methane emissions over the past decade inferred from satellite data and surface observations*, Turner et al., Geophysical Research Letters (preprint), 2016 – http://onlinelibrary.wiley.com/doi/10.1002/2016GL067987/pdf

[268] Frankenberg C, et al. (2011) Global column-averaged methane mixing ratios from 2003 to 2009 as derived from SCIAMACHY: Trends and variability. J Geophys Res 116(D4):D04302.

[269] Turner et al, 2016. *A large increase in U.S. methane emissions over the past decade inferred from satellite data and surface observations*, Turner et al., Geophysical Research Letters (preprint), http://onlinelibrary.wiley.com/doi/10.1002/2016GL067987/pdf

[270] Caulton 2013. Toward a better understanding and quantification of methane emissions from shale gas development www.pnas.org/cgi/doi/10.1073/pnas.1316546111

the overall increase in methane concentrations is unclear. One study has suggested that a plausible figure is around 40%.[271]

283. It is argued that technology can avoid or reduce the amount of fugitive emissions. Methane emissions during the flowback period can in theory be reduced by up to 90% through Reduced Emission Completions (REC) technologies. Indeed, the lower range of emissions estimates produced by Howarth and Ingraffea reflect the use of best technology to also minimise routine venting and leaks at well sites, and fugitive losses during liquid unloading and processing. However, technologies are not always economically viable or practicable. For example, REC technologies require that pipelines to the well are in place *prior* to completion which may not always be possible. The use of better storage tanks and compressors and improved monitoring for leaks also requires an industry willing to pay for the required investments.

284. Reduced Emission Completions (RECs) equipment is now compulsory in the US, and would be expected to be obligatory in the UK. However, the use of emissions-minimising technology and operation may be constrained by economic feasibility, whilst geological characteristics and regulation may also limit emissions minimisation.[272]

Regulation and Risk Management

285. Regulation is one way that society expresses its preferences for distributing the potential risks and benefits associated with any industrial or economic activity across society (including between current and future generations). It reflects the way in which we apply the precautionary principle[273] and how we value nature and other dimensions of the world that have no market value.

286. Given the requirement of commercial companies to maximise profit as a primary goal (and therefore seek to externalise social and environmental costs as much as possible),[274] regulation is important to protect the public interest and ensure that commercial operators behave ethically and safely. Many well-documented case studies from a variety of sectors describe how the imperative to maximise profit results in companies ignoring warning signals about potential

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[271] Hausmann P et al, 2016. Contribution of oil and natural gas production to renewed methane increase. Atmos. Chem. Phys., 16: 3227–3244.

[272] Balcombe, Anderson, Speirs, Brandon and Hawkes, 2015. Methane and CO2 emissions from the natural gas supply chain. London: Sustainable Gas Institute.

[273] The Precautionary Principle is recognised as guidance to 'err on the side of caution' when an activity is believed to threaten human health or the environment, even if there is some scientific uncertainty. See Tickner and Raffensperger (1998),The Precautionary Principle: A Framework for Sustainable Business Decision-Making, *Environmental Policy,* (5/4) 75–82.

[274] Le Menestrel, M., 2002, 'Economic Rationality and Ethical Behavior. Ethical Business between Venality and Sacrifice', *Business Ethics: A European Review*, (11/2) 157–166.

harms and dangers.[275] The recent comprehensive study by Chernov and Sornette on the concealment of risk information prior to the emergence of industrial catastrophes highlights the need for close public scrutiny and a robust sanctions regime.[276]

287. Companies that face difficulties in securing a profit will be placed under to minimise costs and compromise on safety and ethics, which is why the economic viability of shale gas production is important from a public health perspective.

288. Commonly used regulatory mechanisms are legal constraints that limit or prohibit certain activities; laws that prescribe mandatory safety standards; and liability and tax systems that are designed to align the economic interests of the company with the interests of society. For regulation to work, there must also be: a) mechanisms for monitoring the activities of commercial companies and assessing their impact on people and the environment; and b) the ability to enforce sanctions in the event of negligence or non-compliance with regulation.

Regulation and SGP

289. In line with many other industrial processes and human activities, SGP cannot be considered to risk-free. SGP *will* lead to *some* pollution, and it will have some negative social and economic impacts. The key question is whether the risks and harms are deemed acceptable – both in absolute terms, but also in relation to the potential benefits of SGP.

290. SGP is a particularly difficult industry to regulate for several reasons. Much activity takes place underground and out of sight. The sources and types of potential pollution are many and geographically dispersed, and the leakage of methane into the atmosphere is especially hard to detect. It also concerns large and powerful oil and gas corporations that are known to be hostile to regulation and reluctant to acknowledge risk.[277] In addition, shale gas operations may involve multiple contractors (comprising drilling companies, hydraulic fracturing service companies, chemical suppliers, waste haulers and cement contractors) which makes compliance determination difficult.

291. Much has also been written about the challenges of conducting risk assessments of engineering processes because the difficulty of: a) assessing uncertainties and assigning probabilities and appropriate values for estimations; b) distinguishing between objective knowledge and subjective judgments; c) working with intangibles and temporal data; and d) non-disclosure agreements that allow companies to hold back data required for making risk assessments. An engineering approach to risk assessment will also always result in an incomplete analysis or bias because hazards are also related to psychological, social, institutional and cultural processes that affect perceptions of risks and influence risk behaviours.[278]

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[275] EEA, 2001, *Late lessons from early warnings: the precautionary principle 1896–2000*, Environmental issue report No 22, European Environment Agency.

[276] Chernov and Sornette, 2016. Man-made Catastrophes and Risk Information Concealment. Switzerland: Springer Internaitonal Publichsing

[277] Konschnik KE and Boling MK. Shale gas development: a smart regulation framework. Environ Sci Technol 2014; 48: 8404–8416.

[278] See: Renn et al., 1992). Aven (2012), Aven and Kristensen (2005) Pidgeon (1998)

292. Proponents of SGP claim that SGP is safe if regulated properly. According to PHE, the potential risks from exposure to the emissions associated with shale gas extraction will be low *"if the operations are properly run and regulated"*.[279]

293. There is also a view that regulation in the UK is better than in the USA. For example, he industry-funded Shale Gas Task Force is also satisfied that "current regulations in the UK are adequate and on the whole are more rigorous and robust than those in operation in the US".

294. Similarly, PHE stated that the concerns and problems associated with SGP in the US *"are typically a result of operational failure and a poor regulatory environment"* and that shale gas developers and operators in the UK can be relied upon *"to satisfy the relevant regulators that their proposals and operations will minimise the potential for pollution and risks to public health*".[280]

295. However, no thorough and independent assessment of the adequacy of the regulatory system (including the capacity of regulatory agencies) for shale gas has been conducted in the UK.

An overview of the regulatory system for SGP in England

296. The regulatory system for SGP in England is spread across a number of national and local government agencies. Responsibility for overall coordination of policy on unconventional oil and gas lies with the Department of Energy and Climate Change (DECC), within which the Office of Unconventional Gas and Oil (OUGO) is responsible for encouraging unconventional oil and gas exploration and production.

297. The Department for Environment, Food and Rural Affairs (DEFRA) has lead responsibility for the environmental aspects of shale gas policy, while the Department for Communities and Local Government (DCLG) is responsible for the local planning system. Overall responsibility for climate change and seismicity lies with DECC.

298. The Health and Safety Executive (HSE) which reports to the Department for Work and Pensions is responsible for ensuring safe working practices at and around the wellpad, including safe and proper well construction. Finally, Public Health England have been mandated to provide an overall assessment of the potential threats posed to health by SGP.

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[279] Kibble A, Cabianca T, Daraktchieva Z, Gooding T et al, 2014. Review of the Potential Public Health Impacts of Exposures to Chemical and Radioactive Pollutants as a Result of Shale Gas Extraction. Centre for Radiation, Chemical and Environmental Hazards, Public Health England. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/332837/PHE-CRCE-009_3-7-14.pdf

[280] Kibble A, Cabianca T, Daraktchieva Z, Gooding T et al, 2014. Review of the Potential Public Health Impacts of Exposures to Chemical and Radioactive Pollutants as a Result of Shale Gas Extraction. Centre for Radiation, Chemical and Environmental Hazards, Public Health England. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/332837/PHE-CRCE-009_3-7-14.pdf

299. Once Petroleum Exploration Development Licences have been granted by DECC to operators, giving them rights to drill for shale gas,[281] operators must obtain planning permission from the local Minerals Planning Authority (usually located in the planning departments of county councils).

300. The operator must also consult the Environment Agency (EA), an executive non-departmental public body sponsored by DEFRA, which is responsible for regulation of air emissions, protection of water resources (including groundwater aquifers and surface water) and issuing the required permits related to, among other things, water abstraction; wastewater discharge; management and disposal of mining wastes, including radioactive material; and flaring and venting. An environmental impact assessment is now required to be submitted by operators to the EA and planning authority.

301. If planning permission is granted, the HSE must be notified at least 21 days prior to any drilling commencing so that it can assess the well design and ensure the appropriate design and construction of a well casing for any borehole and that measures are in place to control major hazards. It is also expected to continue monitoring operations by reviewing weekly reports submitted by the well operator.

302. One aspect of the regulatory system that has been criticised is that it is fragmented and dispersed over too many agencies. Proponents of SGP argue that this results in delays and inefficiencies. The industry-funded Shale Gas Task Force has therefore recommended that a new, bespoke regulator be created for onshore underground energy and assume the current responsibilities of the EA, HSE and DECC. They also recommend that while local issues like traffic, noise, visual impact and traffic continue to fall under the remit of local authorities, there should be a statutory duty p[laced on them to consult with the new regulator when assessing any planning applications.

303. In arguing that a new bespoke regulator would allow for the required expertise and skills to be developed, the Task Force implicitly admits that the existing levels of capacity and expertise are currently inadequate. However, while there may be a need to strengthen regulatory capacity, a single and centralised bespoke regulator for shale gas clearly runs the risk of regulatory capture, especially if it is to be partly funded by fees from commercial operators (as recommended by the industry-funded Task Force).

304. In terms of detailed standards and best practice guidelines for SGP, the United Kingdom Onshore Operators Group (UKOOG), the representative body for UK onshore oil and gas companies. Recommendations for good practice are also set out in a report produced by the Royal Society and Royal Academy of Engineering report.[282]

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[281] The licences also cover conventional exploration and production of hydrocarbons.
[282] Royal Society and Royal Academy of Engineering, 2012. Shale Gas Extraction in the UK: a review of hydraulic fracturing.

305. In terms of the government, draft technical guidance produced by the EA are similarly limited to exploratory HVHF, vague and not legally binding.[283] Draft technical guidance published was published by the EA in 2013 to clarify which environmental regulations apply to the onshore oil and gas exploration and what operators need to do to comply with those regulations is similarly only guidance.[284] This guidance was put out to public consultation have yet to be announced. A 'regulatory roadmap' published by DECC in December 2015 provides an overview of regulation and best practice related to the licensing, permitting and permissions process for onshore oil and gas *exploration*, development and production, including shale gas.

306. Because SGP is a new activity in the UK, legislation and guidance are expected to evolve. To some extent, it is not possible to specify safety and good practice standards until some exploratory drilling and fracking has taken place. It is notable, however, that in seeking to encourage SGP in the UK, the government has sought to deregulate the industry.

307. For example, new legislative text written in the UK Infrastructure Act, 2015 (under Section 4A) have changed the definition of fracking in a way that may allow SGP activity to bypass previously agreed safeguards. Fracking is now defined as the hydraulic fracturing of shale which involves, or is expected to involve, the injection of 'more than 1,000 m^3 of fluid at each stage, or expected stage, or more than 10,000 m^3 in total.[285]

308. According to Gillfillam and Haszeldine, there is no explanation as to how or why these numbers were chosen, or why volumes of fluid are chosen at all as the basis for defining fracking. By this new definition, almost a half of the gas wells which were hydraulically fractured in the US over this decade would now *not* be classified as "fracked".

309. The 2015 Infrastructure Act has also relaxed the requirement for shale companies to seek permission of home owners to drill under their land.

310. Finally, the government has also decreed that planning permission must now be determined within 16 weeks of an application. Furthermore, if a planning authority fails to meet this deadline or rejects an application on grounds that are inconsistent with the local plan or national guidance, the applicant may appeal and be awarded costs. This change is highly significant because it prevents local authorities from being able to conduct proper risk and impact assessments and because it all but severely inhibits public participation from the planning

[283] DECC, 2013. Regulatory Roadmap: Onshore Oil and gas Exploration in the UK Regulation and Best Practice. Available at https://www.gov.uk/government/publications/regulatory-roadmap-onshore-oil-and-gas-exploration-in-the-uk-regulation-and-best-practice.

[284] Environment Agency, 2013b. Draft Technical Guidance for Onshore Oil and Gas Exploratory Operations. https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCIQFjAA&url=https%3A%2F%2Fconsult.environment-agency.gov.uk%2Ffile%2F2582905&ei=vB4PVff2FeOW7AbGooHAAQ&usg=AFQjCNHGvQ4f2PVbU94Stn9qS9XksN7n9Q

[285] Hydraulic fracturing at a well pad for horizontal shale gas wells is not a "one shot" process, but is performed in stages, as the length of the boreholes usually exceeds several kilometres. Sections of 20-40 metres are blocked off along the horizontal well (packed) and then fracked in stages.

process. The EA also now has to submit reports about environmental risk to councils within sixteen-weeks.

Concerns about the regulatory system

Risk and impact assessments

311. Currently in the UK, shale gas operators are seeking permission to conduct exploratory fracking and relatively small scale production in a few sites. The process for application involves conducting environmental risk and impact assessments, as well as other impact assessments including those related to noise and traffic.

312. In 2015, Lancashire County Council rejected two planning applications submitted by Cuadrilla to conduct exploratory fracking. Cuadrilla appealed the decision and the dispute between the council and the company formed the basis for a Public Inquiry which took place in early 2016 under the auspices of the Planning Inspectorate. The Inquiry raised a number of issues about risk and impact assessments.

313. The first issue concerns the fact that risk and impact assessments are not conducted in a comprehensive and integrated manner. This includes a lack of requirement for a comprehensive social and economic assessment which would assess the impact of SGP on other economic activities such as tourism and agriculture. Related to this was an absence of an assessment of the opportunity costs that are incurred by SGP.

314. The second issue is that the applications in Lancashire only involved an assessment of the risks and potential impact of limited exploratory fracking on two sites, and did not involve an assessment of the potential risk and impact of SGP activity in the scenario of full-scale SGP. This has led some critics to describe the process for approving applications and assessing impact as a 'salami-slice approach' which avoids any cumulative, holistic and comprehensive assessment of the impact of SGP.

Design and construction of wells

315. Generally speaking, the UK adopts a 'goal-setting approach' to regulation in which operators are encouraged to demonstrate to regulators that risks are 'as low as reasonably practicable'. This is designed to encourage operators to move beyond minimum standards in a continuous effort for improvement. In this approach, companies are trusted to be both honest and competent in the way they operate and report to regulators. The role of independent monitoring or independent verification of operator reports is limited.

316. This is exemplified by the system for ensuring that wells are adequately and safely designed and constructed. The system involves an 'independent and competent person' who is charged with examining the integrity and quality of well design and construction. However, the full independence of this person is constrained by the fact that s/he is often paid for or employed by

the operator. In addition, the review and examination of well specifications and design is conducted as a paper exercise and based on information supplied by the operator. As such, there is no mandatory and independent oversight of the *actual construction* of wells, nor provision for unannounced spot checks of well integrity across the lifecycle of a well, including after abandonment.

317. Independent inspection for well integrity was recommended by the Royal Society and Academy of Engineering. Even the industry-funded Shale Gas Task Force noted that it is important not to rely solely on self-monitoring and self-reporting by the operator, and that "regular (and sometimes random) visits and inspections by the regulators" is advisable. The Task Force also recommend that there should be community involvement in an oversight role in this monitoring and public disclosure of the results of well inspections. However, mandatory and independent inspection of wells was rejected during the passage of the Infrastructure Act on the grounds that the current regulatory system is adequate.

Drilling

318. When it comes to drilling, the current regulations appear to be unclear and inadequate, particularly given the faulted nature of the UK geology and the experience of fracking in Preese Hall.

319. As noted earlier, there are reasons why drilling should avoid any geological faults (especially major faults) on the way to the target shale. Operators should therefore ensure that they have optimal data about the geology before and during drilling. This means carrying out the necessary geophysical surveys in advance of drilling; possibly developing new techniques for imaging faults within thick shale sequences; and closely inspecting seismic data during drilling.

320. The apparent negligence that took place at Preese Hall has been partly mitigated by the introduction of a 'traffic light' system of seismic monitoring during fracking. However, it is not clear if this on its own is sufficient to ensure safe drilling.

321. In terms of protecting groundwater from contamination, current laws and regulations prohibit any drilling in 'source protection zones'. It may however be necessary to go further by, for example, specify minimum stand-off distances from faults (vertically and horizontally) for both wellbores and the target formations to avoid triggering earthquakes, or to prohibit fracking altogether in areas where faults penetrate the full thickness of the overburden.

322. There appears to be little if any research into the potential seismic hazard posed by existing or future injection of wastewater in the UK. Should high volume re-injection activity of flowback fluid be carried out in the UK, it would need be carefully monitored to comply with the established traffic light scheme which will be used to measure for induced seismicity from future fracking operations. In an article written by academics from Edinburgh University, it is strongly recommend that a research based, industry accepted code of best practice to reduce the risk of

environmental contamination be established before any flowback fluid re-injection permits are granted.[286]

Baseline monitoring

323. There should also be adequate baseline monitoring before both drilling and fracking commences. Although there are some requirements for baseline monitoring in the best practice guidance and regulations for shale gas, concerns have been raised about the lack of specification over the scope, quality, frequency and standards of pollution monitoring.

324. Concerns about the lack of mandatory minimum standards for the monitoring of air pollutants, including fugitive methane emissions, is justified by the fact that there is currently no data regarding the amount of gas vented by existing oil and gas operations in the UK.[287]

325. The Infrastructure Act requires a period of groundwater monitoring prior to the commencement of fracking. The non-binding UKOOG Code of Practice also commits companies to some baseline monitoring, while the Shale Gas Task Force recommends that "baseline monitoring – for ground, air and water – should begin when a site has been identified, before the environmental permitting and planning have been obtained" They also recommend that "monitoring of gas, casing pressure and soil should take place for the duration of operations on a well".

326. The composition and potential toxicity of fracking fluid has received much public attention. The industry-funded Shale Gas Task Force recognises that while the exact composition of additives may be 'commercially sensitive' and that commercial confidentiality may promote innovation, it also recognises that the public needs to be reassured and recommends that the EA creates a public document of agreed limits of acceptable additives and that it conducts testing "at regular intervals" so that the public can be reassured that there is no risk to public health.

Reduced emissions or green completions

327. When it comes to 'reduced emission completions', guidance published by the EA makes this a recommended practice. The industry-funded Shale Gas Task Force notes that the US has recently mandated the use of green completions, and recommends that the same policy be adopted in the UK for 'production wells'. However, they explain that 'green completions' are not feasible for 'exploratory wells' that will require some flaring of gas.

For compressor stations, local regulation may be able to establish setbacks, maximum noise levels, fencing and landscaping requirements, and enhanced standards for units adjacent to residential areas.

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[286] Haszeldine S, Gilfillan S and O'Donnell M, 2016. UK Failing to Learn US Lessons on Fracking Wastewater. http://www.talkfracking.org/news/uk-failing-to-learn-u-s-lessons-on-fracking-waste-water/
[287] Stamford and Azpagic, 2014. Life cycle environmental impacts of UK shale gas. Applied Energy 134 (2014) 506–518

Abandoned wells

328. According to current guidance, before wells can be abandoned, they must be securely sealed to prevent leakage from within the well bore. Cement is pumped into the production casing and a steel cap is fitted to the top of the well to seal it off. Operators are also required to have a closure and rehabilitation plan (to restore the site to a state similar to that before drilling) which must be agreed by the EA before decommissioning begins. Operators will not be allowed to surrender their permit until the EA is satisfied that there is no ongoing risk to the environment.

329. However, at present, it is not clear who will monitor wells for leakage after they have been abandoned.

330. Even the industry-funded Shale Gas Task Force notes that the Government needs to "clarify where responsibility for the continued monitoring and documentation of sealed-off sites should lie". They also state that "it is not clear who is responsible for any issues around an abandoned well if the operator has gone out of business at the time when a leak or contamination has been identified", and that even currently, "there is little monitoring of abandoned wells" in the UK.

331. In setting out to reassure the public about this issue, the industry-funded Task Force is comfortable with the proposal that wells be inspected two to three months after the concrete plugs have been inserted into the well, and that further inspections focus on soil monitoring and groundwater monitoring "at a suitable recommended interval" and "if there is any reason to believe that well integrity might be compromised".

332. In the US, weak requirements for the independent and adequate monitoring of plugged and abandoned wells has raised concerns given that wells may leak (gas and liquid) for up to thirty years after they have been plugged and abandoned.[288]

Management of wastewater and deep injection

333. At present, specifications about the treatment and disposal of wastewater remain unclear. The recommendation of the industry-funded Shale Gas Task Force is simply that Operator Environmental Impact Assessments (EIAs) 'should clearly set out the proposed arrangements for the disposal of waste water, clearly identifying the disposal routes for all waste streams, including wastes generated from waste water treatment processes'.

334. Recently published draft guidelines for the onshore oil and gas sector outline the EA's current position on wastewater management in England and Wales. This includes aiming to: a)

[288] Kang M, Kanno CM, Reid MC, Zhang X et al, 2014. Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. PNAS vol. 111 no. 51: 18173–18177, doi:10.1073/pnas.1408315111

reduce the amount of waste generated; b) encourage the reuse of waste fluids wherever possible; and c) reduce the need for freshwater and water treatment facilities. For contaminated flowback fluids, the guidance states that re-use is the preferred option. If flowback fluid cannot be re-used, it must be sent to an appropriate permitted waste facility for treatment and disposal.

335. It also states that the EA will "generally not permit the re-injection of flowback fluid for disposal into any formation" *although* the "re-injection of flowback fluid for disposal is not necessarily prohibited and may be permissible where, for example, it is injected back into formations from which hydrocarbons have been extracted and will have no impact on the status of water bodies or pose any risk to groundwater." This new position is a distinct contrast to a previous position of prohibiting the disposal of flowback fluid by re-injecting it into the shale strata.[289]

336. The Shale Gas Task Force also believes that *"there may be situations and circumstances – where the geology is suitable – where deep injection is a sensible, cost effective and popular preferred means of waste disposal"* but recommends that *"a careful analysis should be made of the geological conditions, together with the amount of water and speed at which the water is pumped, relating to any particular site before a decision is taken to dispose of wastewater by deep injection".*

337. In the US, re-injection is the most common and economically viable solution to deal with flowback waste waters but, in addition to induced earthquakes, the practice has also resulted in environmental contamination through surface spills and leaky wells. [290]

338. A review by Ellsworth (2013) of injection-induced earthquakes associated with SGP concludes that earthquakes can be induced by both hydraulic fracturing and the sub-surface disposal of wastewater.[291] Within the central and eastern United States, the earthquake count has increased dramatically over the past few years. Several cases of earthquakes (associated directly with fracking) were large enough to be felt but too small to cause structural damage have been reported. However, most of the concern centers on the injection of wastewater, and not fracking itself. He argues that better knowledge of the stress and pressure conditions at depth; the hydrogeolgic framework, including the presence and geometry of faults; and the location and mechanisms of natural seismicity are needed to develop a predictive understanding of the hazard posed by induced earthquakes. Industry needs clear requirements under which to operate, regulators must have a firm scientific foundation for those requirements, and the public needs assurance that the regulations are adequate and are being observed.

339. The potential permitting of injection for flowback fluids in England and Wales is particularly concerning as there is a complete lack of research on the compositions of the waste water and

[289] http://energyandcarbon.com/uk-failing-lessons-fracking-waste-water/#_ftn24
[290] http://energyandcarbon.com/uk-failing-lessons-fracking-waste-water/#_ftn24
[291] Ellsworth W, 2013. Injection-induced earthquakes, *Science* **341** (6142), doi: 10.1126/science.1225942.

potential chemical reactions in the subsurface. If the UK is to dispose of high-volume flowback fluids from shale gas by using re-injection into geological formations, much further research into the potential risks of the process and how to reduce them is required.

340. It is also worth considering the volumes involved. The existing onshore conventional industry in the UK disposes of approximately 12 million cubic metres of produced water every year. The Institute of Directors forecasts a UK shale industry developing, between now and 2030, 100 pads with 40 multilateral wells each, with each pad using 0.5 million cubic metres of water. [292] Assuming that 50% of this fracturing fluid flows back, a total of 27 million cubic metres of flowback will need to be disposed of during this period. In comparison, as stated above, the conventional industry will dispose of as much produced water every two-and-a-bit years.

Sanctions regime

341. An effective sanctions regime in the event of negligence or non-compliance with safety standards and best practice is an important aspect of the regulatory system.

342. The proposal to require companies to secure a bond to insure them against the cost of any potential liability has not been adopted as policy. There are inadequate safeguards to prevent fracking operators from passing the ownership and liability of commercially non-viable wells onto subsidiary companies that subsequently go into administration shortly after.

343. Although the industry has stated that they will develop an insurance mechanism to cover full liability in the event of a pollution incident, this remains a non-binding promise and would, in any case, offer weaker protection than a legally-mandated bond agreement that would cover the costs of decommissioning, faulty well remediation, and compensation for possible pollution of water resources, depreciation of land and house prices, and earthquake damage.

Capacity and expertise of regulatory bodies

344. It is frequently stated that regulation of the oil and gas industry is of the highest standard in the UK and more effective than in the US.

345. Such statements should not be taken at face value. As noted above, there are uncertainties, and potential weaknesses in the proposed regulatory system for SGP. The last few years have also seen deep cuts to the budgets, staffing and expertise of a range of regulatory agencies, while central government's strong support for SGP has seen certain powers diminished in regulatory bodies, including local government.

346. The regulatory system in the US varies considerably from state to state, and in some instances, regulatory standards may be more stringent than in the UK. It is worth noting that New York State has actually banned SGP on the grounds that it would be harmful to health.

[292] Institute of Directors, 2013. Getting shale gas working.

347. The erosion of the capacity of public interest and regulatory agencies is especially worrying. Local government budgets and capacity have been particularly hard hit, including those related to public health. According to the National Audit Office, there has been a 37% estimated real-terms reduction in government funding to local authorities 2010-11 to 2015-16.[293] Once changes to council tax income are factored in, there has been an estimated 25% real-terms reduction in local authorities' income from 2010-11 to 2015-16. There has also been a 46% budgeted real-terms reduction in spending on planning and development services between 2010-11 and 2014-15.

348. Net spending by local authorities on public services (excluding spending on police, fire and rescue, education, public health and a small component of social care) in England has been cut by 20.4% in real terms between 2009-10 and 2014-15. Some of the service areas with the largest cuts were planning and development (cut to less than half its original level), regulation and safety, housing, and transport (all of which were cut by at least 30%). Local authorities are expected to face further cuts to revenues per person of 4.1% in 2015-16 (excluding specific grants for mandatory housing benefit payments and education, public health, fire and police services).[294]

349. As far as local government's responsibility for deciding whether or not a particular proposed drilling and fracking application should go ahead, reasonable concerns exist around county councils lacking in-house geological expertise or the time and money to seek independent advice. All too often they are reliant on the information provided by the applicant.

350. Budget cuts to the EA have also been severe. According to UNISON, there has been a 16% cut in the total grants made in 2009-10 compared to 2013-14.[295]Taking into account an inflation rate of 11%; this is equivalent to a cut of nearly 25% in real terms. Thousands have jobs have been lost in this period.[296]

351. Furthermore, the EA's experience of hydrogeology – which tends to be limited to the upper few hundreds of metres of bedrock – may be insufficient to deal with the environmental hazards of SGP.

352. The HSE budget was cut by 13% from £228 million in 2009–2010 to £199 million in 2011–2012. Its staff numbers were reduced by 22% from 3,702 in 2010 to 2,889 up to 2012.[297] According to HSE chief executive Geoffrey Podger in 2010, 'the number of staff has fallen drastically, from over 4,200 a decade ago to around 2,200'. The HSE's Annual Report & Accounts

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293 From National Audit Office report, The impact of funding reductions on local authorities, November 2014. https://www.nao.org.uk/wp-content/uploads/2014/11/Impact-of-funding-reductions-on-local-authorities.pdf

294 David Innes and Gemma Tetlow, 2015. Central Cuts, Local Decision-Making: Changes in Local Government Spending and Revenues in England, 2009--- 10 to 2014--- 15

295 https://www.unison.org.uk/at-work/water-environment-and-transport/key-issues/cuts-at-the-environment-agency/

296 http://www.endsreport.com/article/41653/environment-agency-cuts-surviving-the-surgeons-knife

297 Watterson and Dinan, 2015. Health Impact Assessments, Regulation, and the Unconventional Gas Industry in the UK: Exploiting Resources, Ideology, and Expertise. Journal of Environmental and Occupational Health Policy 0(0) 1–33.

for 2014/15 furthermore states how it has delivered a 40% real term budget reduction from 2011/12 to 2014/15. According to its Business Plan for 2015/16, grants provided by government to fund certain activities are planned to reduce by over £82m in 2015/16 compared to 2011/12. The extent to which drilling will be properly scrutinised by specialist wells inspectors from the HSE (or any new bespoke regulator) is therefore a contentious point.

353. The Task Force recommend that the Government establishes a National Advisory Committee of independent academic experts with a remit to examine, collate and evaluate health impacts associated with shale gas operations in the UK once operations have begun and data from the first wells becomes available.

Climate change and health

Global Warming and climate change

354. The production and consumption of energy has been an important ingredient for the remarkable improvements in human health witnessed over the past two centuries. However, because of global warming, fossil fuel now presents a major threat to human health.[298]

355. The average global land and sea surface temperature has risen by about 1°C since pre-industrial times.[299] Lags in the response of the climate system to historical emissions mean that the world is already committed to further warming over the coming decades.

356. The primary cause for this increase in temperature is the release of GHG emissions. About 70% of all GHG emissions can be linked to the burning of fossil fuel for the production of energy services, goods or energy extraction.[300] Agriculture, deforestation and cement use are also important causes of global warming.

357. The metric commonly used to quantify the total amount of GHGs in the atmosphere is 'giga tonnes of CO_2 equivalent' ($GtCO_2e$). This converts quantities of methane and other GHGs into a measure that is equivalent to the dominant GHG which is carbon dioxide.

358. About 1600 $GtCO_2e$ has been emitted into the atmosphere since 1870. In 2010, annual global GHG emissions were estimated at 49 $GtCO_2e$.[301]

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[298] Global warming caused by human activity is an incontrovertible fact, backed by empirical evidence and sound scientific theories. It is driven by GHGs trapping heat within the earth-atmosphere system.

[299] http://www.metoffice.gov.uk/research/news/2015/global-average-temperature-2015

[300] Victor, D, Zhou, D, Ahmed, E et al. Introductory Chapter. in: O Edenhofer, R Pichs-Madruga, Y Sokona, (Eds.) Climate change 2014: mitigation of climate change contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY; 2014

[301] Summary for policymakers. in: O Edenhofer, R Pichs-Madruga, Y Sokona, (Eds.) Climate change 2014: mitigation of climate change contribution of Working Group III to the Fifth Assessment Report of the

359. Global GHG emissions from heat and electricity production and transport have tripled and doubled respectively since 1970, whereas the contribution from agriculture and land-use change has slightly reduced from 1990 levels.[302]

360. The rise in temperature increases the amount of energy in the earth-atmosphere system as well as the amount of water in the atmosphere, both of which lead to changes in the weather.[303]

361. CO_2 (and some other pollutants) also causes ocean acidification which damages marine organisms and threatens freshwater supplies across the world. The effect of ice melting and water expansion (caused by temperature rise) and subsequent sea level rise is another important dimension of global warming.

Impacts on global health

362. The impacts of global warming on health can be direct (eg, heatwaves; extreme weather events such as a storm, forest fire, flood, or drought; and sea level rise), or indirect, mediated through the effects of climate change on, amongst other things, food production systems, economies, forced migration and increasing levels of conflict and violence.

363. There are already observed impacts of climate change on health. There is a well-established relationship between extreme high temperatures and human morbidity and mortality[304] and strong evidence that heat-related mortality is rising across a range of localities.[305]

364. Heatwaves and increases in the incidence of extreme heat are projected under all future scenarios of climate change.[306] Heat poses significant risks to occupational health and labour productivity in areas where people work outdoors for long hours in hot regions.[307] Loss of

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Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY; 2014

302 Bruckner, T, Bashmakov, I, Mulugetta, Y et al. Energy Systems. in: O Edenhofer, R Pichs-Madruga, Y Sokona, (Eds.) Climate change 2014: mitigation of climate change contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY; 2014

303 McCoy D and Hoskins B, 2014. The science of anthropogenic climate change: what every doctor should know. BMJ 2014*;* 349 doi: http://dx.doi.org/10.1136/bmj.g5178

304 Aström, C, Orru, H, Rocklöv, J, Strandberg, G, Ebi, KL, and Forsberg, B. Heat-related respiratory hospital admissions in Europe in a changing climate: a health impact assessment. BMJ Open. 2013; 3: e001842

305 Smith, KR, Woodward, A, Campbell-Lendrum, D et al. Human health—impacts adaptation and co-benefits. Climate change 2014: impacts, adaptation, and vulnerability Working Group II contribution to the IPCC 5th Assessment Report. Cambridge University Press, Cambridge, UK and New York, NY, USA; 2014

306 Patz, JA, Campbell-Lendrum, D, Holloway, T, and Foley, JA. Impact of regional climate change on human health. Nature. 2005; 438: 310–317

307 Kjellstrom, T, Holmer, I, and Lemke, B. Workplace heat stress, health and productivity—an increasing challenge for low and middle-income countries during climate change. Global Health Action. 2009; 2 (10.3402/gha.v2i0.2047.)

agricultural productivity through impaired labour will amplify direct climate change by impacting negatively on food production.[308]

365. One study estimates that the effects of heat could cost China and India by as much as US$450 billion in 2030.[309] Although there may be modest reductions in cold-related deaths in some pars of the world; at the global scale, these benefits will be outweighed by heat-related mortality.[310]

366. Heatwaves also carry risks for the wider environment. For example, the summer 2010 heatwave in Russia[311] was accompanied by more than 25,000 fires over an area of 1·1 million hectares[312] and raised concentrations of carbon monoxide, nitrogen oxides, aerosols, and particulates (PM_{10}) across European Russia.

367. Changing weather patterns will affect the incidence of certain vector-borne diseases. For example, rising temperatures and changes in precipitation pattern will alter the distribution of disease vectors such as mosquitoes carrying dengue or malaria. Dengue fever for example has 390 million recorded infections each year, and the number is rising. Changing weather patterns will also increase waterborne diseases such as cholera in the coming decades. [313]

368. Airborne particulate matter (PM) produced from the combustion of coal and oil also impinges negatively upon health by causing respiratory and cardiovascular disease. Household and ambient air pollution is estimated to have been responsible for 7 million additional deaths globally in 2012.[314] In the UK, around 40,000 deaths are attributable to exposure to outdoor air pollution.[315] The OECD estimates that the value of lives lost and ill health due to ambient air pollution in OECD countries, plus India and China, is more than $3·5 trillion annually (about 5% gross world product), with India and China accounting for 54% of this total.[316]

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[308] Porter, JR, Xie, L, Challinor, AJ et al. Food security and food production systems. in: CB Field, VR Barros, DJ Dokken, (Eds.) Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA; 2014: 485–533

[309] DARA and the Climate Vulnerability Forum. Climate vulnerability monitor 2012: a guide to the cold calculus of a hot planets. Fundacion DARA Internacional, Barcelona; 2012

[310] Ebi, K and Mills, D. Winter mortality in a warming climate: a reassessment. Wiley Interdiscip Rev Clim Change. 2013; 4: 203–212

[311] Russo, S, Dosio, A, Graversen, RG et al. Magnitude of extreme heat waves in present climate and their projection in a warming world. J Geophys Res D Atmospheres. 2014; 199: 500–512

[312] Ryazantzev, S. Demographic and socio-economic consequences of heat wave and forest fires of 2010 in European Russia. Ecol Life. 2011; 5: 80–85

[313] Lipp, EK, Huq, A, and Colwell, RR. Effects of global climate on infectious disease: the cholera model. Clin Microbiol Rev. 2002; 15: 757–770

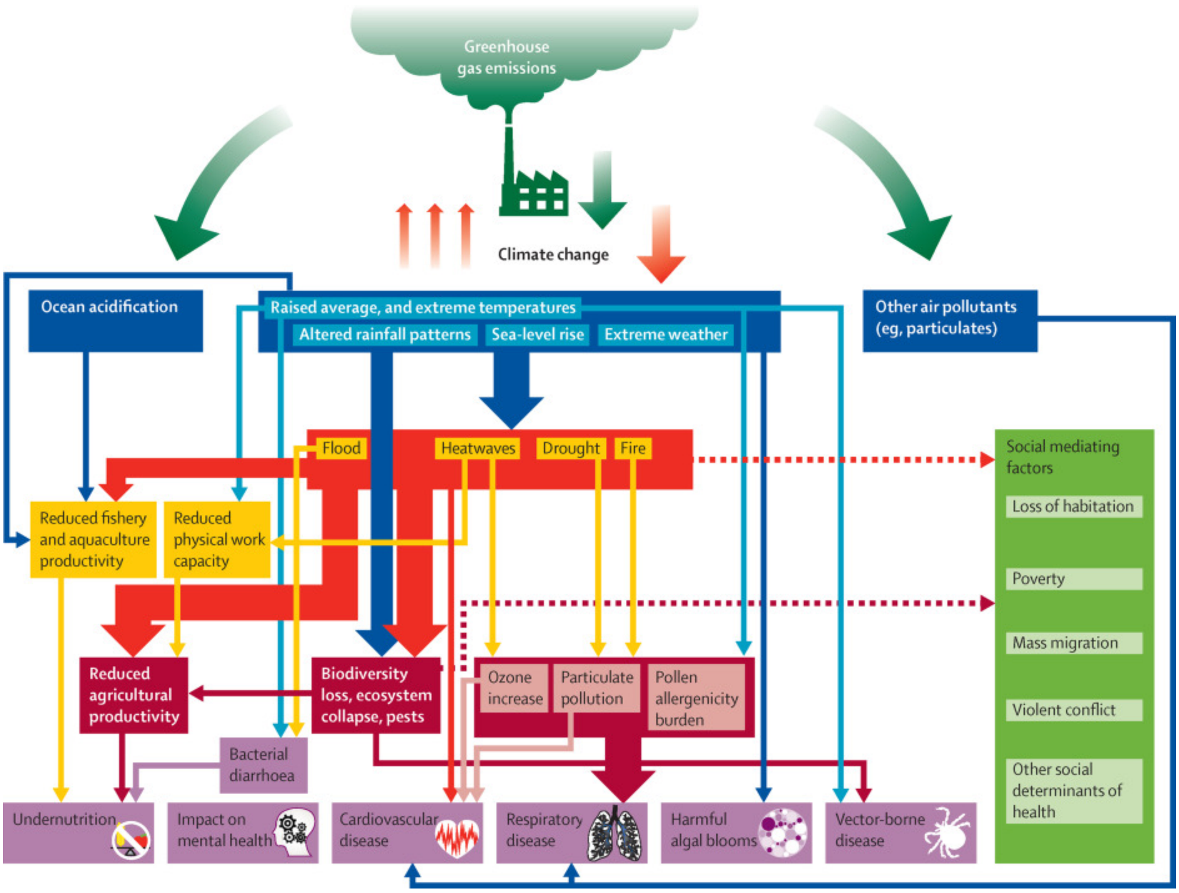
[314] WHO. Burden on disease from air pollution in 2012. http://www.who.int/phe/health_topics/outdoorair/databases/FINAL_HAP_AAP_BoD_24March2014.pdf; 2014.

[315] Royal College of Physicians. *Every breath we take: the lifelong impact of air pollution*. Report of a working party. London: RCP, 2016.

[316] Organisation of Economic Co-operation and Development, 2014.The cost of air pollution: health impacts of road transport. Paris: OECD.

369. By altering temperature and precipitation frequency, climate change can further elevate levels of atmospheric particulate matter and ground level ozone in certain regions.[317] [318] [319] One study estimates that ozone-related acute mortality in the USA could rise by 4·5% from 1990 to 2050 through climate change alone.[320]

370. Most climate-related health impacts are mediated through complex ecological and social processes as shown in the diagram below.



371. The impact of climate change on pushing up food prices and affecting food availability and affordability will be substantial, especially for regions and populations that are already food insecure.[321] Policies related to polices on food stocks, reactions to food prices by producer

[317] Giorgi, F and Meleux, F. Modelling the regional effects of climate change on air quality. C R Geosci. 2007; 339: 721–733

[318] Tagaris, E, Manomaiphiboon, K, Liao, K-J et al. Impacts of global climate change and emissions on regional ozone and fine particulate matter concentrations over the United States. J Geophys Res, D, Atmospheres. 2007; 112: D14312

[319] Jiang, H, Liao, H, Pye, HOT et al. Projected effect of 2000–2050 changes in climate and emissions on aerosol levels in China and associated transboundary transport. Atmos Chem Phys. 2013; 13: 7937–7960

[320] Knowlton, K, Rosenthal, JE, Hogrefe, C et al. Assessing ozone-related health impacts under a changing climate. Environ Health Perspect. 2004; 112: 1557–1563

[321] Grace, K, Davenport, F, Funk, C, and Lerner, AM. Child malnutrition and climate in Sub-Saharan Africa: An analysis of recent trends in Kenya. Appl Geogr. 2012; 35: 405–413

countries, and demand for land to hedge against climate shifts may further increase volatility within the global food system and compound the threat of reduced food productivity for many populations.[322]

372. Added to the challenge of worsening food security, is the critical factor of water availability. Groundwater resources are already in a critical state in many regions[323] [324] and increased exposure to drought-like meteorological conditions over the coming decades is a considerable threat. One analysis shows that climate change, when combined with population changes, could lead to 1·4 billion additional person drought exposure events per year by the end of the century.[325]

373. The potential impact of increased frequency of floods, storm surges and hurricanes is exemplified by the 6000 plus fatalities that resulted from typhoon Haiyan in the Philippines in 2013. Floods also have long-term and short-term effects on wellbeing through disease outbreaks, mental health burdens, and dislocation. [326] [327] The involuntary displacement of populations as a result of extreme events has major health and policy consequences as evidenced recently in the UK.

374. The IPCC concludes that climate change will directly affect poverty, resource uncertainty and volatility, and the ability of governments to fulfil their obligations to protect settlements and people from weather extremes.[328] [329]

375. The continued movement of migrant populations into cities, the potential for climate hazards in high-density coastal mega-cities, and impaired air quality create significant public

[322] Porter, JR, Xie, L, Challinor, AJ et al. Food security and food production systems. in: CB Field, VR Barros, DJ Dokken, (Eds.) Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA; 2014: 485–533

[323] Taylor RG, Scanlon B, Doll P et al. Ground water and climate change. Nature Clim Change. 2013; 3: 322–329

[324] Schewe, J, Heinke, J, Gerten, D et al. Multimodel assessment of water scarcity under climate change. Proc Natl Acad Sci USA. 2014; 111: 3245–3250

[325] Watts N, Adger WN, Agnolucci P et al, 2015. Health and climate change: policy responses to protect public health. The Lancet, Vol. 386, No. 10006, p1861–1914

[326] Ahern, M, Kovats, RS, Wilkinson, P, Few, R, and Matthies, F. Global health impacts of floods: epidemiologic evidence. Epidemiol Rev. 2005; 27: 36–46

[327] Paranjothy, S, Gallacher, J, Amlôt, R et al. Psychosocial impact of the summer 2007 floods in England. BMC Public Health. 2011; 11: 145

[328] Adger, WN, Pulhin, JM, Barnett, J et al. Human security. in: CB Field, VR Barros, DJ Dokken, (Eds.) Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA; 2014: 755–791

[329] Olsson, L, Opondo, M, Tschakert, P et al. Livelihoods and poverty. in: CB Field, VR Barros, DR Dokken, (Eds.) Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY; 2014: 793–832

health challenges, not least for migrants themselves.[330] [331] The effects of food and resource insecurity, migration, displacement, uncertainty and poverty all combine to make climate change a threat to peace and human security.[332]

376. Scientists are also highly confident that climate change is bleaching coral on reefs worldwide; affecting river flows; forcing plant and animal species towards the poles and to higher elevations around the world; and negatively impacting those living in the Arctic. There has been a negative effect on the growth in productivity of some key crops, including for wheat and maize.

377. Although the magnitude and nature of future health impacts are hard to predict with precision, unless action is taken to stop the net increase in GHG emissions, all plausible futures resulting from anticipated emissions trajectories will expose the global population to serious health consequences.

378. Furthermore, there is a real risk of unforeseen interactions and the amplification of known climate risks. Of great concern is the risk of crossing thresholds and tipping points which would produce accelerations in warming and larger-than-expected chances of catastrophic outcomes.[333] [334]

379. According to the Lancet-UCL Commission on Climate Change and Health, climate change could be “sufficient to trigger a discontinuity in the long-term progression of humanity”[335] and that on the basis of current emission trajectories, “temperature rises in the next 85 years may be incompatible with an organised global community”.[336]

380. Whilst initially certain regions and communities will suffer disproportionately, the interconnected and global nature of climate systems, ecosystems and human society will mean that all parts of the world will be affected.[337] Regions that might be less affected by the direct effects of climate change will be negatively affected by the economic and social disruption in those regions that are more directly affected.[338]

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[330] McMichael, C, Barnett, J, and McMichael, AJ. An ill wind? Climate change, migration, and health. Environ Health Perspect. 2012; 120: 646–654
[331] Black, R, Arnell, NW, Adger, WN, Thomas, D, and Geddes, A. Migration, immobility and displacement outcomes following extreme events. Environ Sci Pol. 2013; 27: S32–S43
[332] Gleditsch, NP. Whither the weather? Climate change and conflict. J Peace Res. 2012; 49: 3–9
[333] Rockström, J, Steffen, W, Noone, K et al. Planetary boundaries: exploring the safe operating space for humanity. Ecol Soc. 2009; 14: 32
[334] Lenton, TM, Held, H, Kriegler, E et al. Tipping elements in the Earth's climate system. Proc Natl Acad Sci USA. 2008; 105: 1786–1793
[335] Watts N, Adger WN, Agnolucci P et al, 2015. Health and climate change: policy responses to protect public health. The Lancet, Vol. 386, No. 10006, p1861–1914
[336] Anderson, K and Bows, A. Beyond ‘dangerous’ climate change: emission scenarios for a new world. *Philos Trans A Math Phys*. Eng Sci. 1934; 2011: 20–44
[337] Smith KR, Woodward A, Campell-Lendrum D et al. Human health—impacts adaptation and co-benefits. Climate change 2014: impacts, adaptation, and vulnerability Working Group II contribution to the IPCC 5th Assessment Report. Cambridge University Press, Cambridge, UK and New York, NY, USA; 2014
[338] Adger WN, Pulhin JM, Barnett J et al. Human security. in: CB Field, VR Barros, DJ Dokken, (Eds.) Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects contribution of

381. Although there is some uncertainty in understanding the earth's future climate system and how further global warming will impact on weather patterns, biodiversity, food production and water stress, the risks outlined above indicate the need to take climate change as a serious and potentially existential threat to organised and peaceful civilisation.

Global GHG emissions, carbon budgets and international policy

382. It is difficult to forecast with any certainty the future pattern of GHG emissions, energy use or global temperature rise. However, climate scientists have constructed various risk models that relate GHG emission targets to future temperature rise. These 'integrated assessment models' are highly complex and incorporate multiple assumptions about costs, markets, human behaviour, population growth and the physics of climate change.

383. A key output of their analyses has been the construction of 'global carbon budgets' that are associated with various probabilities for limiting the rise in global temperatures to below a defined limit. The table below shows the estimated carbon budget for the period 2011 to 2100 that would be consistent with various probabilities of limiting global warming to less than 1.5°C and 2°C.

Cumulative carbon dioxide emissions consistent with warming targets at different levels of probability

Net anthropogenic warming	**< 1.5°C**			**< 2°C**		
Probability	66%	50%	33%	66%	50%	33%
Cumulative CO_2 emissions from 2011 -2100 ($GtCO_2e$)	400	550	850	1000	1300	1500
Cumulative CO_2 emissions from 1870 ($GtCO_2$ e)	2250	2250	2550	2900	3000	3300

(Source: IPCC Fifth Assessment Report, 2014)

384. To have a better than 66% chance of limiting global warming to below 2°C, cumulative GHG emissions from 2011 onwards would need to be limited to around 1,000 (630–1180) $GtCO_2e$.[339] To have a better than 50% chance of limiting global warming to below 1.5°C, cumulative GHG emissions from 2011 onwards would need to be limited to around 500 $GtCO_2e$.[340] A global

Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA; 2014: 755–791

[339] Clarke L, Jiang K, Akimoto K et al. Assessing transformation pathways. In Edenhofer, Pichs-Madruga, Sokona (Eds.) Climate change 2014: Mitigation of climate change contribution of Working Group III to the Fifth Assessment Report of the IPCC. Cambridge University Press; 2014

[340] Clarke L, Jiang K, Akimoto K et al. Assessing transformation pathways. In Edenhofer, Pichs-Madruga, Sokona (Eds.) Climate change 2014: Mitigation of climate change contribution of Working Group III to the Fifth Assessment Report of the IPCC. Cambridge University Press; 2014

carbon budget of about 850 $GtCO_2e$ for the period 2011-2100 would equate with an "unlikely" (<33%) chance of staying below 1.5°C.

385. Estimates about future emissions trajectories, including carbon cycle feedbacks, and their impact on global temperatures are full of uncertainty, being based on multiple assumptions and limits in knowledge. However, many models used may be optimistic because they tend to assume relatively early peaks in global emissions and that 'negative emission technologies' will be practically and economically viable in removing CO_2 from the atmosphere.[341] [342]

386. The 850 to 1000 $GtCO_2e$ budget range is commonly used in policy circles. This refers to the global budget we have for all emissions from all sectors for the period 2011 to 2100. To understand what emissions are available from 2016 onwards, it is necessary to subtract those emissions released between 2011 and 2016. Based on CDIAC data, this is *at least* 150 $GtCO_2$ which leaves a budget of 700-850 $GtCO_2e$ for the period 2016-2100.

387. Although energy production is a major source of GHG emissions, agriculture, deforestation, and cement use are also important sources. An optimistic estimate of emissions from deforestation and cement process for 2016 to 2100 would be in the region of 60 $GtCO_2$ and 150 $GtCO_2$ respectively, leaving an 'energy-only' global budget of 490-640 $GtCO_2e$ for the period 2016 to 2100.[343]

388. Combining optimistic assumptions about curtailing deforestation and cement emissions with the IPCC's headline budget of 1,000 $GtCO_2$ would equate with global reductions in energy-related emissions of at least 10% per annum from 2025, transitioning rapidly towards zero emissions by 2050.[344] [345]

389. Current GHG emissions trends are not reassuring. Globally, since 2000, GHG emissions have been rising at around 2% every year, powered largely by growth in China and other emerging economies.[346] Overall global energy demand grew by 27% from 2001 to 2010, largely concentrated in Asia (79%), the Middle East and Africa (32%), and Latin America (32%) on the basis of territorial accounting.[347] However, consumption-based accounting shows that most of

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[341] Anderson K, 2015. On the Duality of Climate Scientists. **Nature Geoscience, DOI: 10.1038/ngeo2559.**
[342] Fuss, S. *et al.* Betting on negative emissions. *Nature.* **4.** 850-853 (2014)
[343] Anderson K, 2015. On the Duality of Climate Scientists. Nature Geoscience, DOI: 10.1038/ngeo2559.
[344] Krey, V, Masera, G, Blanford, T et al. Annex II: metrics & methodology. in: O Edenhofer, R Pichs-Madruga, Y Sokona, (Eds.) Climate change 2014: mitigation of climate change contribution of Working Group III to the Fifth Assessment Report of the IPCC. Cambridge University Press; 2014
[345] Even stabilising CO_2e concentrations to between 450–650 ppm (which would be consistent with 2-4°C of warming), the global emission rate would need to fall by 3–6% per year, a rate that so far has only been associated with major social upheaval and economic crisis. See: Beyond 'dangerous' climate change: emission scenarios for a new world. *Philos Trans A Math Phys*. Eng Sci. 2011(1934): 20–44
[346] Summary for policymakers. In: Edenhofer, Pichs-Madruga, Sokona (Eds.) Climate change 2014: Mitigation of climate change contribution of Working Group III to the Fifth Assessment Report of the IPCC. Cambridge University Press; 2014.
[347] Bruckner, T, Bashmakov, I, Mulugetta, Y et al. Energy Systems. in: O Edenhofer, R Pichs-Madruga, Y Sokona, (Eds.) Climate change 2014: mitigation of climate change contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY; 2014

the recent growth in energy expenditure has been driven by consumption in high-income regions.[348]

390. According to one assessment, energy expenditure in non-OECD countries will double by 2035 from 2010 levels, with OECD countries seeing a 14% increase over the same period.[349] Once again, most of the future projected growth in energy expenditure is expected to be driven by consumption in high-income regions.

391. At the current global emission rate, the 'carbon budget' described above could be depleted within as little as 24 years, possibly sooner. The window of opportunity to prevent potentially catastrophic climate change is therefore small.

392. The Paris Agreement (December 2015) has been heralded as marking a new level of international commitment to addressing the threat of global warming. The principal aim of the Agreement is to hold "*the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change".*

393. The Paris Agreement also notes that countries will aim to reach global peaking of GHG emissions *"as soon as possible"*, whilst recognising that peaking *"will take longer for developing country parties".*

394. However, the voluntary pledges made by individual countries to reduce their GHG emissions do not match the ambition of the Agreement's goal. The US, for example, has only pledged to reduce its emissions by 12-19% from 1990 levels. Even if all countries deliver on their current pledges, the predicted level of global warming arising from cumulative emissions would be between 2.8°C and 4°C above pre-industrial levels.

395. Analysis of the latest UN pledges by Climate Action Tracker suggests that global emissions are on track to reach 53-59 $GtCO_2e$ in 2030, which is significantly above present global emissions of about 48 $GtCO_2e$. Furthermore, there are gaps between current policy projections and country pledges meaning that current policies are not strong enough to achieve these conservative pledges.[350]

396. The gap between the climate science and the actual policies and plans to reduce GHG emissions is therefore considerable. This partly reflects a reluctance to abandon our dependence

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[348] Barrett J, Le Quéré, Lenzen M, Peters G, Roelich K, and Wiedmann T, 2011. Consumption-based emissions reporting. Memorandum submitted by UKERC (CON 19). http://www.publications.parliament.uk/pa/cm201012/cmselect/cmenergy/writev/consumpt/con20.htm;.

[349] International Energy Agency (IEA). World energy outlook 2013. IEA, Paris; 2013

[350] See: http://climateactiontracker.org/global/173/CAT-Emissions-Gaps.html

on both fossil fuels and unsustainable consumption patterns. It also reflects a faith in future technologies being developed to sequester GHGs from the atmosphere.[351]

The role of shale gas in mitigating global warming

397. Proponents of natural gas argue that it is a clean form of energy when compared to coal and oil and that its use for electricity generation instead will help reduce the rate at which the carbon budget is depleted. In order to assess the potential future impact of natural gas on carbon budgets and global warming, life cycle analyses (LCAs) are conducted to determine the amount of GHGs emitted across all stages of gas production and end-use.

398. These LCAs are inevitably influenced by a number of variables which produce a wide range of measures of the global warming potential of natural gas. The variables include: i) the amount of fugitive emissions released directly into the atmosphere; ii) whether the gas produced is liquefied and transported before use (because both liquefaction and transportation required energy); iii) the efficiency of the power stations used to convert gas into electricity; iv) the use of CCS technologies; and v) the time horizon over which the global warming potential of methane and carbon dioxide are assessed. When comparing the global warming potential of gas against other energy sources, the relative efficiencies of coal power stations and the impact of gas on coal, oil and renewable energy are also relevant.

399. A key factor in LCAs of natural gas is fugitive emissions. According to Howarth, while for a given unit of energy produced, carbon dioxide emissions are less for shale gas and conventional natural gas than those for oil and coal, the total GHG footprint of shale gas may be greater than other fossil fuels when methane emissions are included.[352]

400. Sanchez and Mays (2015) modelled what leakage rate of natural gas in electricity generation would cause CO_2e emissions of natural gas to become equivalent to those of coal, and found that the leakage rate must be lower than 3.9% in the life-cycle of its production, distribution and use, when looked at over a 20-year time horizon. Above this threshold the GHG footprint advantage of natural gas is eliminated.[353]

401. The GWP of shale gas relative to conventional natural gas is contentious. Burnham et al's analysis of lifecycle GHG emissions concluded that shale gas life-cycle emissions were 6% lower

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[351] In particular, biomass energy carbon capture and storage (BECCS) has become prominent after Paris. BECCS involves covering large areas of the planet with bio-energy crops that will absorb carbon dioxide through photosynthesis. Periodically these crops would be harvested; processed for worldwide travel; and eventually combusted in thermal power stations. The carbon dioxide would then be extracted from the waste gases, compressed (almost to a liquid); pumped through large pipes (potentially over very long distances); and finally stored deep underground in various geological formations (e.g. exhausted oil and gas reservoirs or saline aquifers).

[352] Howarth R, 2015. Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy. Energy and Emission Control Technologies 2015:3 45–54

[353] Sanchez N & Mays D, 2015 Effect of methane leakage on the greenhouse gas footprint of electricity generation, *Climatic Change* November 2015, Volume 133, Issue 2, pp 169-178

than conventional natural gas (23% lower than gasoline and 33% lower than coal). However, the range in values for shale and conventional gas overlap, so the difference is not statistically significant.[354] Key factors, highlighted by this study, are the assumptions made about the use of 'green technologies' and the rate of upstream fugitive emissions, as well as the relative efficiency of power stations.

402. Laurenzi and Jersey's (2013) LCA of shale gas from the Marcellus shale for power generation found that a typical gas life cycle yields 466 kg CO2eq/MWh (80% confidence interval: 450−567 kg CO2eq/MWh) of GHG emissions. Their results were influenced strongly by the estimated ultimate recovery (EUR) of the well and the power plant efficiency (their results were based on electricity generation at a combined cycle gas turbine power plant and a 100 year time horizon). They found that the carbon footprint of Marcellus gas is 53% (80% CI: 44−61%) lower than coal, and comparable to that of onshore conventional natural gas.[355] Operations associated with hydraulic fracturing constituted only 1.2% of the life cycle GHG emissions.

403. Weber and Clavin's review of the LCA literature concluded that the upstream carbon footprints of different types of gas production are likely to be similar. However, they found that the upstream footprint is less than 25% of the total carbon footprint of gas, and note that the efficiency of producing heat, electricity, and transportation services is of equal or greater importance when identifying emission reduction opportunities. They also note, as do most other authors, that better data are needed to reduce the uncertainty in natural gas's carbon footprint, and that understanding system-level climate impacts of shale gas through shifts in national and global energy markets is also important and requires more detailed energy and economic systems assessments.[356]

404. Regardless of any measure of the GWP of natural gas per unit of energy service (e.g. electricity or heating), the total volume of gas production and consumption is also important. For example, according to McLeod at el's (2014) model, if gas prices are kept low (as anticipated) a global warming potential of methane of 72 over 20 years generates overall energy system GHG emissions in 2050 that are 6% higher than in 2010.[357]

405. Using simulations of five state-of-the-art integrated assessment models of energy–economy–climate systems, McJeon et al (2014) indicate that a future scenario of globally abundant gas would lead to an overall increase in 'climate forcing'.[358] The models found that

[354] Burnham, A. et a, 2012. Life-cycle greenhouse gas emissions of shale gas, natural gas,coal, and petroleum. Environ. Sci. Technol. 46, 619–627.
[355] Laurenzi IJ. And Jersey GR, 2013. Life cycle greenhouse gas emissions and freshwater consumption of Marcellus shale gas. Environ. Sci. Technol. 47, 4896–4903.
[356] Weber C and Clavin C. Life cycle carbon footprint of shale gas: Review of evidence and implications. Environ. Sci. Technol. 2012, 46, 5688−5695.
[357] McLeod et al, 2014, Emissions Implications of Future Natural Gas Production and Use in the US and in the Rocky Mountain Region, Environ Sci Technol 2014;48, 13036-13044
[358] McJeon, H et al (2014) Limited impact on decadal-scale climate change from increased use of natural gas, Nature 514, 482–485, doi:10.1038/nature13837

while gas substitutes largely for coal, it also substitutes nuclear and renewable energy, and tends to increase economic activity. This finding echoes the 'Golden Age of Gas' scenario presented by the IEA which indicated a projected 3.5°C warming as a consequence.[359]

406. There is evidence that while US shale gas displaced coal use for electricity generation (and helped reduce GHG emissions from the energy sector by 12% between 2005 and 2012), the displaced US coal was exported and burnt abroad.[360] As a result, CO_2e emissions from the combustion of all fossil fuels generated from the US actually rose by approximately 10%.[361]

407. The point about new gas reserves *increasing* the threat of global warming by simply adding to the available stock of fossil fuel was made by DECC's former Chief Scientific Advisor who noted: "*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.*"[362]

408. The Environmental Report published by DECC in relation to the 14th onshore licensing round also points to the dangers of shale gas merely displacing coal and oil rather than replacing them altogether as a source of energy.[363] Similarly, the Lancet-UCL Commission on Climate Change and Health noted that the time when fuel switching could decarbonise the global economy sufficiently quickly to avoid dangerous climate change has almost certainly passed.

409. Fossil fuel 'reserves' are known fossil fuels that are economically 'extractable'. The volume of fossil fuel reserves is therefore partly a function of the fossil fuel price which is highly volatile. Some reports distinguish between the concepts of 'carbon bubble' being a financial issue, and 'unburnable carbon' being a technological issue.

410. The estimated amount of 'unburnable carbon' ranges from 49% to 80% of overall reserves.[364] McGlade and Ekins (2015) concluded that 50% of existing global gas reserves are 'unburnable' (including >80% of global potential unconventional gas reserves), in addition to a third of oil and 80% of coal reserves.[365]

411. McGlade and Ekins (2015) note that CCS has the largest effect of any technology on cumulative fossil fuel production levels. CCS could enable countries to continue to include fossil

[359] IEA, *World Energy Outlook 2011 Special Report: Are We Entering A Golden Age of Gas?*, International Energy Agency, Paris, France, 2011
[360] Broderick and Anderson, 2012. Has US Shale Gas Reduced CO2 Emissions? Examining recent changes in emissions from the US power sector and traded fossil fuels, Tyndall Manchester, University of Manchester
[361] US EIA December 2014 Monthly Energy Review
[362] DJ MacKay & TJ Stone Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use (DECC, 2013)
[363] Strategic Environmental Assessment for Further Onshore Oil and Gas Licensing Environmental Report (December 2013) – p.88.
[364] Budinis, Krevor, MacDowell et al, 2016. Can Technology unlock 'unburnable' carbon? London: Sustainable Gas Institute
[365] McGlade, C. and Ekins, P. (2015) The geographical distribution of fossil fuels unused when limiting global warming to 2°C, Nature 517, 187—190, doi:10.1038/nature14016

fuels in their energy mix and therefore can unlock assets that would otherwise be stranded.[366] According to the World Energy Outlook (2012), without CCS, less than a third of global carbon reserves can be burnt in the 2°C scenario.[367] One study estimated that CCS could enable 65% of reserves to be used instead of 33%.[368]

412. Regardless of the availability and affordability of safe CCS technologies, there is still a limited carbon budget and a timeframe within which the world needs to achieve net zero GHG emissions. According to Howarth (2015), the imperative to reduce methane emissions to slow global warming over the coming few decades means that the only path forward is to reduce the use of all fossil fuels as quickly as possible. There is no bridge fuel, and switching from coal to shale gas is accelerating rather than slowing global warming.

413. A key argument against the development of more shale gas reserves is that investment in efficiency and renewables would be a more cost-effective solution than coal-to-gas substitution.

414. One concern is that the deployment of natural gas risks delaying the deployment of renewable energy systems. According to Zhang et al (2016), this could offset all the potential climate benefits derived from replacing coal energy systems with natural gas energy systems.[369] They note that the risks are higher when the natural gas energy system is inefficient and the coal energy system is efficient. In addition, they highlight the importance of the choice of time horizon because methane is a much stronger GHG than carbon dioxide but which acts for a much shorter time.[370]

415. Zhang et al's analysis shows that natural gas *can* provide climate benefit as a 'bridging fuel' if the coal energy system is inefficient; the natural gas energy system is efficient; the natural gas leakage rate is low; and the evaluation time horizon for the global warming potential of methane is longer than 40 years. However, in the absence of CCS, natural gas use cannot provide the deep reductions in GHG emissions needed to prevent dangerous climate change. They warn that "If the introduction of natural gas substantially delays the transition to near-zero emission systems, there is potential that the introduction of natural gas could lead to greater amounts of warming than would have occurred otherwise.

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366 IPCC (2005). IPCC Special Report: Carbon capture and storage. Available online: www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf[Accessed 05/02/2016].
367 IEA (2012). World Energy Outlook 2012. www.worldenergyoutlook.org/publications/weo-2012/
368 Budinis, Krevor, MacDowell et al, 2016. Can Technology unlock 'unburnable' carbon? London: Sustainable Gas Institute
369 Zhang X, Myhrvold N, Hausfather Z, Caldeira K (2016) Climate benefits of natural gas as a bridge fuel and potential delay of near-zero energy systems, Applied Energy 167 (2016) 317–322
370 According to Howarth, the GWP of methane is 86 more than that of carbon dioxide when averaged over 20 years (for two equal masses of the gases emitted into the atmosphere).

The UK: Greenhouse Gas Emissions and energy policy

The UK's carbon budgets

416. The UK Government's position on GHG emissions is based on recommendations made by the Committee on Climate Change (CCC). The CCC's first report, which built on the IPCC's fourth assessment report (2007), concluded that economic and political constraints made it impossible to ensure *"with high likelihood"* that a temperature rise of more than 2°C can be avoided. Instead it proposed to reduce the risk of *"extremely dangerous climate change"* (defined as a 4°C temperature rise this century) to *"very low levels"*. [371]

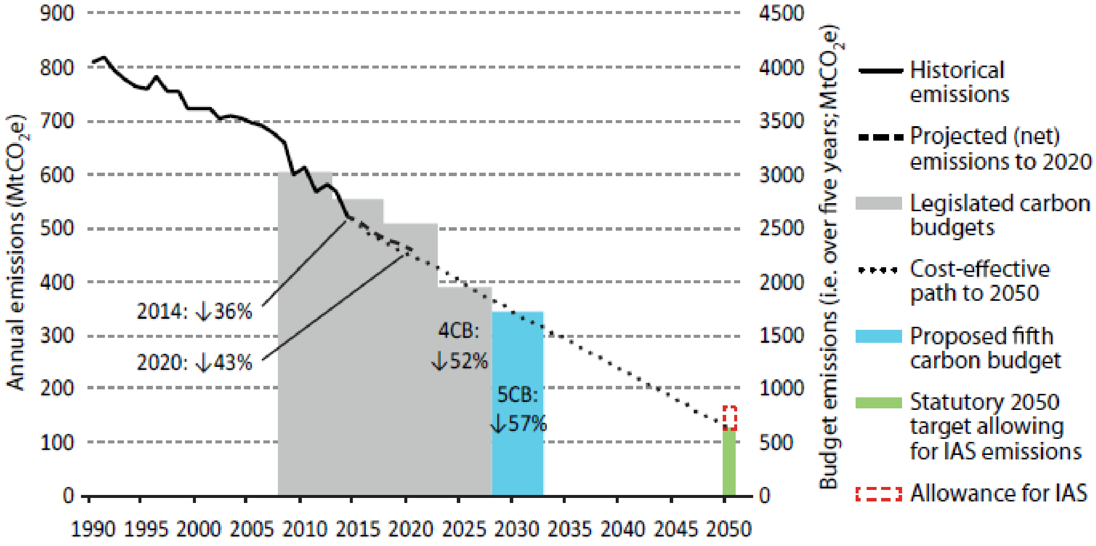
417. The CCC then offered two national and century-wide carbon budgets, along with a mid-century obligation to reduce emissions in 2050 by 80% compared to 1990 levels. The two budgets were related to a 56% and a 63% chance of exceeding 2°C. The UK government chose to accept a 63% chance of exceeding 2°C.

418. The CCC has subsequently published a series of carbon budgets for a set of sequential five-year periods. The fourth carbon budget (2023-2027) capped emissions at 1,950 $MtCO_2e$, which is equivalent to an average 52% below 1990 levels. The fifth carbon budget (2028-2032)[372] which was proposed at 1,765 $MtCO_2e$ (including emissions from international shipping) and which would limit annual emissions to an average 57% below 1990 levels is due to be formally enacted into law in July 2016.

419. The target set for the first carbon budget (2008-2012) has been met, and the target for the second budget (2013-2018) is on course to be met.[373]

420. The past and projected emissions trajectory is shown in the diagram below. The trajectory proposed by the CCC involves a smooth and incremental reduction in emissions across the economy of around 13 $MtCO_2e$ (3%) per year from 2014 to 2030.

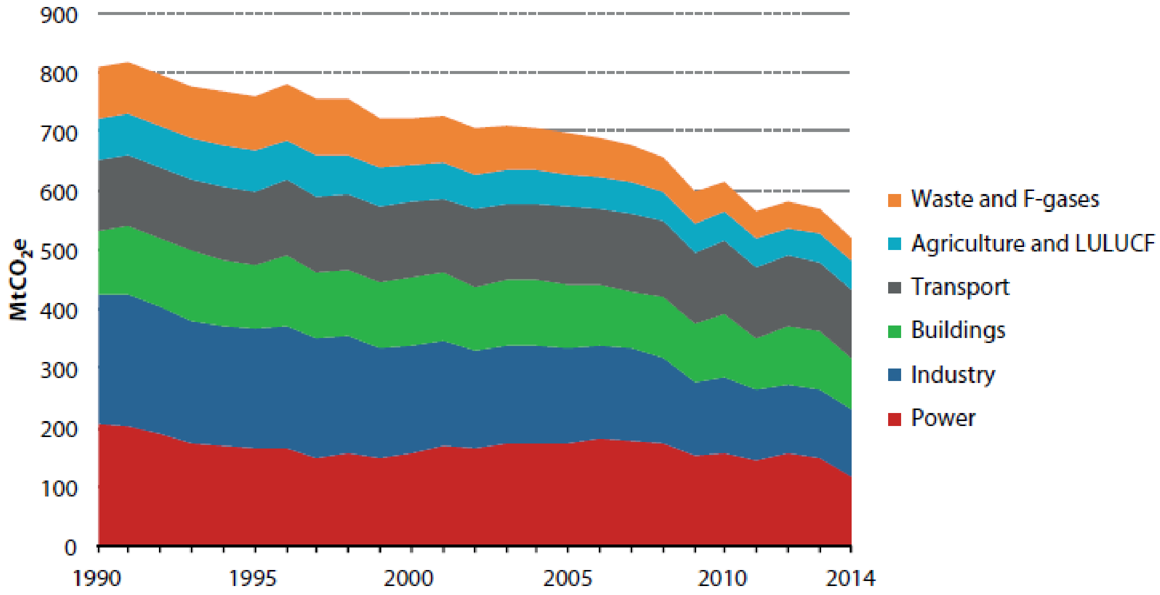
[371] CCC, 2008. Building a low-carbon economy - the UK's contribution to tackling climate change.
[372] CCC, 2015. The Fifth Carbon Budget – The next step towards a low-carbon economy
[373] The carbon budget for 2014 was 520 $MtCO_2e$, excluding emissions from international aviation and shipping.



Source: DECC (2015) *Final UK greenhouse gas emissions national statistics: 1990-2013*; DECC (2015) Provisional UK greenhouse gas emissions national statistics; DECC Energy Model; CCC analysis.
Notes: Data labels show reductions in annual emissions relative to 1990. Historical emissions are on a 'gross' basis (i.e. actual emissions). Projections and carbon budgets are on the current budget accounting basis: net carbon account excluding international aviation and shipping (IAS), but allowing for IAS to be included in the 2050 target.

421. The pattern of energy production and consumption has shown important changes since 1990, both in terms of GHG emissions, energy mix and energy use. The figure below shows the pattern of UK GHG emissions by sector since 1990. This is a pattern for territorial emissions and does not reflect the GHG emissions of goods and products produced elsewhere but consumed in the UK.

Historical UK emissions of greenhouse gases (1990-2014)



Source: DECC (2015) *Final UK greenhouse gas emissions national statistics: 1990-2013;* DECC (2015) *Provisional UK greenhouse gas emissions national statistics*; CCC analysis.

422. Although the UK's statutory target to reduce GHG emissions by 80% compared to 1990 levels sounds ambitious, there are reasons why the target is inadequate. First, the targets are based on the integrated assessment models of the IPCC which, for reasons described earlier, are believed to be over-optimistic. Second, the budget is arguably based on a dangerous level of risk that accepts a 63% chance of exceeding 2°C.

423. Third, the UK carbon budget represents an unfair share of the global carbon budget, making little allowance for historical responsibility for GHG emissions, or the considerably superior financial and technical capability of the UK compared to most other countries.[374]

424. Fourth, the UK's GHG emissions targets are also calculated as 'territorial emissions' and therefore do not take into account the GHGs emitted elsewhere to produce goods and commodities that are eventually imported into the UK. In the UK, while territorial-based emissions have shown a 19% reduction between 1990 and 2008, consumption-based emissions have increased by 20% in the same period (driven by GHGs embodied in imported products, particularly from China).[375]

425. Finally, the planned reduction of emissions is spread across the period to 2050 rather than front-loaded. This runs counter to the clear message from climate scientists that we need to frontload as much of our GHG emissions reductions as possible. Models reviewed in the IPCC's

[374] Friends of the Earth, 2015. Why the UK must commit to its fair share of emissions cuts ahead of the Paris climate talks. November.
[375] http://www.publications.parliament.uk/pa/cm201012/cmselect/cmenergy/1646/1646vw13.htm

Working Group III Fifth Assessment Report (AR5) indicate that more needs to be spent earlier rather than later if even a moderate value is given to the intermediate and long term future.[376]

426. Early emissions reduction will delay climate disruption and reduce the overall cost of abatement by avoiding drastic and expensive last-minute action. Furthermore, it allows the window of opportunity for the development and deployment of new technologies to be held open for longer. Delayed emission reduction could also force the uptake of riskier and unproven mitigation technologies with increased risk of unintended consequences for human wellbeing and ecosystems.[377]

Trends in energy use

427. The reduction in GHG emissions since 1990 has been put down to a combination of factors: economic recession post-2008; a move away from coal and oil towards gas and renewables in generating electricity; contraction of energy-intensive industries (including iron and steel); improved efficiency of boilers and buildings; a reduction in cattle numbers, synthetic fertiliser application and biodegradable waste sent to landfill; and the implementation of methane recovery systems.

428. However, in spite of improvements in the average fuel efficiency of vehicles, transport sector emissions (excluding emissions from international aviation and shipping) have not decreased substantially and actually increased by 1.1% between 2013 and 2014.[378]

429. In 2014, direct domestic energy consumption in the UK was 142.8 million tonnes of oil equivalent (Mtoe). The two largest sources of fuel were petroleum liquids (86% of which were used for transport) and natural gas (60% of which was used in the domestic sector). Overall, fossil fuels accounted for 84.5% of the UK's energy supply. In terms of end use, the transport sector accounted for 38% of total energy use.[379]

430. UK emissions for 2014 were split between six sectors by the CCC as follows: power/electricity generation (23%), industry (21%), buildings (16%), transport (23%), agriculture and land-use, land-use change and forestry (9%), and waste and fluorinated gases (7%).

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[376] Edenhofer, Pichs-Madruga, Sokona (Eds.) Climate change 2014: mitigation of climate change contribution of Working Group III to the Fifth Assessment Report of the IPCC. Cambridge University Press; 2014.
[377] Mills, E. Weighing the risks of climate change mitigation strategies. Bull At Sci. 2012; 68: 67–78
[378] DECC, 2015. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416810/2014_stats_release.pdf
[379] DECC, 2015. Energy Consumption in the UK. https://www.gov.uk/government/statistics/energy-consumption-in-the-uk

431. In the fourth quarter of 2015, the mix of fuels to generate electricity was: gas (29.7%), renewables (26.9%), coal (19.9%), nuclear (15.6%), and oil and other sources (2.3%).[380]

432. The pattern of primary fuels used to generate electricity in the UK has changed to reflect a lower dependence on coal and a greater reliance on gas and renewable energy. The substitution of coal by gas has been occurring since the major reductions in coal use over 1970-1980; and the so-called 'dash for gas' in the 1990s.

433. The share of coal in UK primary energy consumption has fallen from 40% in 1970 to 16% by 2014, while gas use increased from 5% to 47%. Of the coal used in 2014, nearly 80% was used to generate electricity.[381] Projections to 2030 show that coal generation will fall by 63% from 2015 levels in 2020, and by 96% in 2025. The government has committed to phase out all coal use for electricity generation by 2025.

434. Because most coal plants will have been retired before any substantial production of shale gas occurs, the GHG footprint of shale gas relative to coal is not relevant. Rather, shale gas needs to be compared with other potential sources of electricity and heating including biogas, conventional gas, biomass and renewables.

435. Of the total natural gas consumed in 2011, about 52% was to provide heat for buildings and industry, while 34% was burned in power stations to make electricity.[382] In 2010, 85% of homes were heated by gas.[383]

436. In 2013, 11.2 Mtoe of primary energy use was accounted for by renewables, 75% was to generate electricity, and 15% was used to generate heat.[384] In 2013, 70% of renewable energy came from bioenergy (including wood, wood waste and agricultural by-products), while about a fifth came from wind. Hydro-electric and solar PV contributed less than 10%.

Achieving the UK's 2050 target for GHG emissions reductions

437. The current pattern of GHG emissions sources in 2014 and the statutory target for 2050 are shown in the diagram below.

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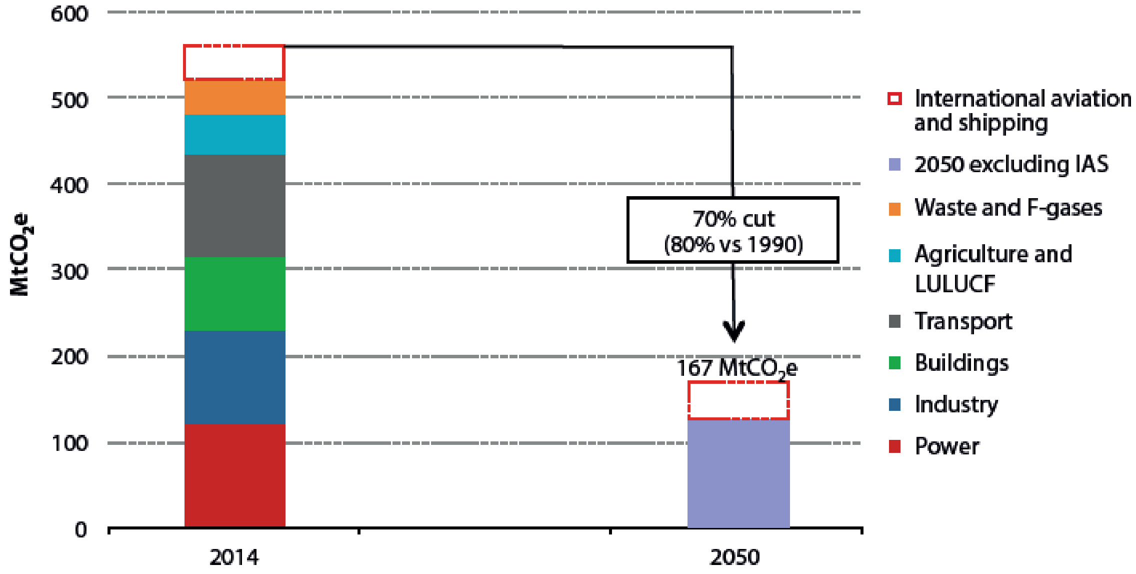
380 Statistics- National Statistics. Energy Trends Section 5: Electricity. [Online]. Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/437802/Electricity.pdf

381 DECC, 2015. Energy Consumption in the UK. https://www.gov.uk/government/statistics/energy-consumption-in-the-uk

382 Department of Energy and Climate Change. (2013). The Future of Heating: Meeting the Challenge. [Online] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/190149/16_04-DECCThe_Future_of_Heating_Accessible-10.pdf

383 National Grid. (2014). UK Future Energy Scenarios; UK Gas and Electricity Transmission. [Online] Available at: http://www2.nationalgrid.com/uk/industry-information/future-ofenergy/future-energy-scenarios/

384 Department of Energy and Climate Change. (2014c). UK Energy in Brief 2014. [Online] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/350941/UK_Energy_in_Brief_2014_revised.pdf



Source: DECC (2015) *Final UK greenhouse gas emissions national statistics: 1990-2013*; DECC (2010) *Final UK greenhouse gas emissions national statistics: 1990-2008*; CCC analysis. **Notes:** International aviation and shipping data are for 2013.

438. DECC's latest interim projection (October 2015) suggests that GHG emissions will fall by 15% between 2014 and 2020, driven largely by a significant reduction in power sector emissions (due to the 2020 renewables target and a shift away from coal). Further reductions are also expected in transport due to the impact of the EU new car and van CO_2 targets for 2020, and from a partial replacement of oil-based fuels with biofuels.[385]

439. However, maintaining progress towards the 2050 target will become increasingly difficult. According to DECC, although the UK is set to meet its carbon budget targets up to the year 2022, achieving the target set for 2027 and beyond "will be much more challenging". Despite primary energy demand being projected to fall 11% over the next 10 years, demand may start to increase again because further improvements in energy efficiency may be insufficient to offset the impact of economic and population growth.

440. The CCC note that DECC's future projections assume that current policies to reduce emissions are delivered in full. However, the CCC have noted in their 2014 and 2015 Progress Reports that a number of policies are at risk of failure due to design and delivery problems, or because they are unfunded. These include the Agricultural Action Plan, policies to improve the fuel efficiency of HGVs, the Renewable Heat Incentive post-2016, Zero Carbon Homes and the Renewable Transport Fuels Obligation. Since then, there has been further weakening of policies, including the cancellation of Zero Carbon Homes.

[385] It remains to be seen what impact the recent referendum result on Europe will have in terms of EU directives that underpin the UK's emissions reductions targets.

441. Three aspects of decarbonisation are crucial: energy efficiency, energy conservation, and a shift to low-carbon electricity.

442. The CCC highlights that reaching the 2050 target would require: a) continued take-up of ultra-low emission vehicles and low-carbon heat (e.g. heat networks and heat pumps); b) improved home insulation; and c) *deep* reductions in emissions from electricity generation. Notably, by 2030, the mean carbon intensity for electricity generation would need to be below 100gCO_2/kWh, and probably as low as 50gCO_2/kWh (compared to 450gCO_2/kWh in 2014 and 200-250gCO_2/kWh expected by 2020).[386] [The November 2015 projections from DECC have a central scenario of 100g/kWh[387], which is at the upper end of the CCC-recommended range].

443. The CCC argue that the critical part played by early decarbonisation of the power generation sector and increased electrification of end-use sectors from 2030 will require a strong policy framework, including electricity market reform[388] and radical changes in energy vectors after 2030 including switching from gas to heat pumps for heating.[389]Industry will also need to be decarbonised through use of electricity or combustion of hydrogen from low-carbon sources.

444. The CCC also emphasises the need to enable the commercialisation of CCS, and for investment in developing heat networks, electric vehicle charging networks and potentially, infrastructure for hydrogen applications. Electricity networks will also need to be strengthened to cope with new demands (e.g. from heat pumps) and increasing generation from low-carbon sources. Options deemed to represent good value investments before 2030 include onshore and offshore wind, ground-mounted solar, and nuclear.[390]

445. Other themes in the CCC's scenario planning for meeting the 2050 target include: agriculture emissions falling due to changed farming practices (e.g. on-farm efficiencies, improved animal fertility), reduced food waste and adjustment of diet towards less carbon-intensive foods; and a switch to sustainable bioenergy providing around 10% of primary energy in 2050. The CCC assumes that demand for international aviation is likely to grow considerably and that there will therefore need to be strong efficiency improvements in that sector.

446. According to the CCC, carbon capture and storage is "very important in meeting the 2050 target at least cost, given its potential to reduce emissions across heavy industry, the power sector and perhaps with bioenergy, as well as opening up new decarbonisation pathways (e.g. based on hydrogen)". The critical issue of CCS is discussed later.

[386] The Committee on climate change. Fourth Carbon Budget Review – technical report – Chapter 2
[387] DECC, 2015. Updated energy and emissions projections: 2015. Nov 18th
[388] Depending on the extent of electrification in transport, heat and other applications, the level of electricity consumption in 2050 could be 50-135% above the level in 2014.
[389] CCC, 2015. The Fifth Carbon Budget – The next step towards a low-carbon economy
[390] CCC, 2015. Power sector scenarios for the fifth carbon budget

The role of gas in generating electricity

447. According to the CCC, to effectively decarbonise power, transport and heat generation by 2050, it will be necessary to decarbonise all new investment by 2020 for power (with the exception of back-up and balancing plant); and by 2035 for transport.

448. The CCC's scenarios for the power sector in 2030 include some role for unabated gas generation to continue, with new nuclear, CCS and renewables meeting increases in demand. However, the CCC's scenario for energy production have now move towards the upper end of the 50-100 gCO_2/kWh range because of delays to new nuclear and CCS projects.[391]

449. Two crucial factors determining the future role of gas are the availability of CCS and the efficiency of gas-fired power stations.

450. An efficient new-build gas-fired electricity power station (combine cycle gas turbines, CCGT) emits around 345gCO_2/kWh (this figure can be higher depending on the efficiency of the particular plant and whether life-cycle emissions are taken into account). To put this in perspective, the life-cycle emissions for mature renewables and nuclear can be in the region of 5-30gCO_2/kWh.[392] However, a scenario of efficient gas power stations combined with CCS could produce lifecycle emissions of 50-80gCO_2/kWh.[393] [394] [395]

451. While substituting coal with gas over the next *nine* years will help reduce carbon emissions, after 2025, if the UK's carbon targets are to be met cost-effectively, the use of gas in power stations would need to decline, especially if they are not fitted with CCS. The majority of the drop in coal generation will be covered by renewables growth, rather than gas. The DECC scenario has gas generation at 76TWh in 2030 which is lower than present. Anything more than this would be incompatible with the UK's climate change goals.

452. According to DECC's projections, beyond 2025, new gas power stations need only to be used as back-up plants at peaks which makes it important that the UK does not build too many new gas power stations and be left with under-used or redundant gas-power station capacity.

453. According to UKERC, the risk of carbon lock-in needs to be considered with modern CCGT plants having a technical lifetime of at least 25 years and policy measures would therefore be

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[391] CCC, 2015. Power Sector Scenarios for the Fifth Carbon Budget.
[392] Turconi R, Boldrin A, Astrup T (2013) Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. Renew Sust Energ Rev 28:555–565
[393] Odeh, Hill and Forster, 2013. Current and Future Lifecycle Emissions of Key 'Low Carbon' Technologies and Alternatives. See https://www.theccc.org.uk/wp-content/uploads/2013/09/Ricardo-AEA-lifecycle-emissions-low-carbon-technologies-April-2013.pdf
[394] Hammond GR, Howard HR and Jones CI, 2013. The energy and environmental implications of UK more electric transition pathways. Energy Policy 52, 103-116
[395] CCC, 2015. Power Sector Scenarios for the Fifth Carbon Budget.

needed to ensure that any CCGTs that are still required by 2040 are either fitted with CCS or operated at much lower load factors.[396]

454. In terms of heat, gas emits approximately 200gCO_2/kWh of heat, a level which also cannot be reconciled with the UK's carbon budget. Consequently, gas has a marginal and rapidly declining role in generating electricity post-2030.

455. In terms of supplying domestic, commercial and industrial heat, neither DECC nor the CCC have been able to develop low-carbon (~2°C) post-2030 scenarios that maintain a significant role for gas.[397]

456. Following recent modelling work[398] designed to analyse a range of possible future energy scenarios the UK Energy Research Centre, concluded that gas is unlikely to act as a cost-effective 'bridge' to a decarbonised UK energy system except for a short period of time from 2015 till about 2020. For this reason, they suggest that it is more appropriate to characterise gas as "a short-term stop-gap until low- or zero-carbon energy sources can come on stream" and that without CCS, "the scope for UK gas use in 2050 is little more than 10% of its 2010 level". [399]

457. CCS emerges as a critical technology if gas is to have a significant role, consistent with UK carbon reduction targets, out to 2050. But even with CCS, there may be limited cost-effective scope for gas use in power generation beyond 2030, and that because any new gas-fired power stations would need to operate on relatively low load factors, the economically viability of investments in such new gas-fired power stations is questionable.

458. The CCC admits that CCS is crucial to meeting the UK's 2050 target for reduced emissions, and recommends that coal and gas CCS be used in conjunction with other low-carbon energy sources. However, uncertainty remains over whether CCS can be deployed at the scale required, at reasonable cost, and with the required level of effectiveness. The government's withdrawal of support for the development of CCS, may therefore compromise the UK's decarbonisation ambitions.

Renewable Energy

459. The CCC explicitly promotes a mixed portfolio approach towards energy security in the near future. Some continued role for fossil fuel in the medium to long term future is implicated, but this is heavily dependent depends on the development of CCS and negative emissions technologies (NETs).

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[396] McGlade C, Pye S, Watson J, Bradshaw M and Ekins P, 2016. The future role of natural gas in the UK. London: UK Energy Research Centre

[397] AEA for the CCC. Decarbonising heat in buildings: 2030–2050

[398] Two models were used. One was used to generate a large number of sensitivity scenarios incorporating a variety of technological, resource and price assumptions and key uncertainties about the development of the future energy system. A second was used to project future UK energy use.

[399] McGlade C, Pye S, Watson J, Bradshaw M and Ekins P, 2016. The future role of natural gas in the UK. London: UK Energy Research Centre

460. What is clearer is the central importance of renewable energy, and nuclear power.[400] [401] The notes presented here do not cover the subject of nuclear energy which produces fewer GHG emissions than fossil fuels, but which carries risks in terms of radioactive waste, accidents and the proliferation of nuclear weapons. The exorbitant costs associated with Hinckley C also point to nuclear energy presenting considerable economic and fiscal threats to society.

461. The contribution of RE to the total energy mix in the UK is growing. Since 2010 the UK has increased its generation from renewables 25TWh to 73TWh in 2015.[402] Currently renewables supply around 20-25% of UK electricity and DECC estimates that they will supply more than 40% by 2030.[403] In the National Grid's 2015 projection of the UK's Future Energy Scenarios, RE supplies 11-30% of the annual power demand by 2030.[404]

462. However, groups such as Friends of the Earth believe that an electricity mix comprising over 75% renewables by 2030 would be a feasible and more appropriate target.

367. The industry-funded Shale Gas Task Force has argued that we should embrace "a long term evolutionary approach" towards renewable energy, rather than "a short term revolution". The reasons they give for this slow approach include: a) inadequate grid infrastructure for absorbing wind, tidal and wave energy; b) public disapproval of bigger onshore transmission pylons; c) investors having limited funds; d) renewable energy being economically unviable; e) the intermittency of RE; f) RE technology being under-developed and socially unacceptable.

463. However, according to the CCC, it will be possible "to ensure security of supply in a decarbonised system with high levels of intermittent and inflexible generation".[405] Parts of the solution include achieving greater inter-connection to systems beyond the UK; making it easier for energy demand to respond more effectively and efficiently to short-term price signals; increasing the capacity for electricity storage; and ensuring that back-up capacity is flexible enough to increase generation without having to run part-loaded.

464. Two studies used by the CCC indicate that the UK could generate over 80% of electricity demand from renewables without jeopardising security of supply, through the use of storage, interconnectors and demand side management.[406] [407]

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[400] International Energy Agency. Energy technology perspectives 2012. IEA, Paris; 2012
[401] International Energy Agency. Coal medium-term market report 2012. IEA, Paris; 2012
[402] DECC, 2015. Updated energy and emissions projections. Annex J
[403] DECC, 2015. Updated energy and emissions projections. Annex J
[404] National Grid. (2015). UK Future Energy Scenarios; UK Gas and Electricity Transmission. [Online] Available at:
http://investors.nationalgrid.com/~/media/Files/N/National-Grid-IR/reports/future-energy-scenarios-2015.pdf
[405] CCC, 2015. Power sector scenarios for the fifth carbon budget
[406] Garrad Hassan, 2011. UK generation and demand scenarios for 2030. March.
[407] Poyry, 2011. Analysing technical constraints to renewable generation to 2050.

465. Renewables are providing electricity at increasingly lower costs. Recent agreed contracts for future power (Contracts for Difference) signed by onshore wind and solar (£79/MWh for 15 years), and offshore wind (£115/MWh for 15 years) are already cheaper than new nuclear (£92.50/MWh for 35 years).[408] Offshore wind's cost is also falling fast; and projected to cost less than £100/MWh by 2020.[409] The CCC say onshore wind and large-scale solar will be cheaper than new gas which pays its pollution costs before 2025.[410] Furthermore, since wind and solar produce electricity at zero marginal cost, they have the potential to lower electricity prices.[411]

466. The CCC notes that the rate and extent of change needed to stay within our carbon budget indicates a need for much greater efforts to reduce our consumption of energy as well as rapidly expanding on the delivery of renewable energy.

467. The feasibility of moving rapidly towards a decarbonised energy system has been substantiated by other studies. Two studies for the states of New York[412] and California[413] have demonstrated the possibility of moving towards an economy driven totally by RE sources (largely solar and wind) in a cost-effective way using technologies that are commercially available today within the next 15-35 years.

Energy security

468. One of the important arguments in favour of SGP is that it will improve the UK's energy security. Energy security typically has two dimensions: ensuring the lights stay on, and avoiding being overly-reliant on other countries for energy.

469. Since 1999, there has been a sharp rise in fossil fuel imports in the UK. The highest level of imported energy since 1974 was reported in 2013 due to an ongoing decline in domestic oil and gas production. Nearly half of the UK's net energy supply came from imports.[414]

470. About 46% of the UK's use of natural gas comes from the North Sea. The remainder is imported[415] from Norway (about 30%), the Netherlands (about 8%) and Belgium (about 4%).[416] The remaining 20% of imported gas is liquefied natural gas (LNG), mainly from Qatar.

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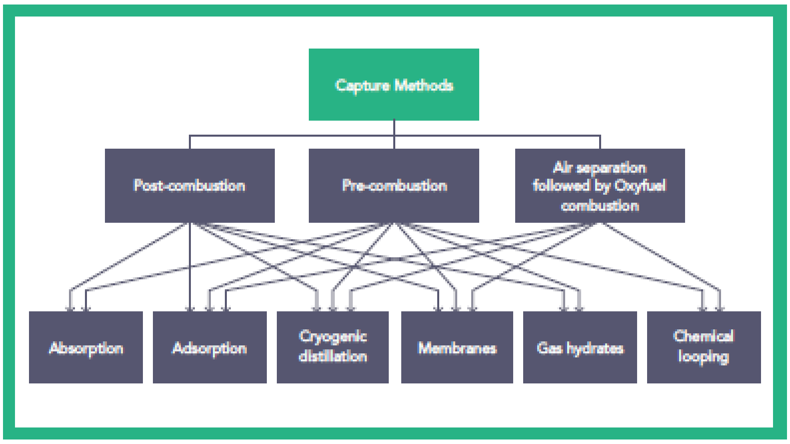
408 CCC, 2015. Power Sector Scenarios for the 5th Carbon Budget. Box 4.1
409 Catapult, 2015. Cost of wind energy falls sharply. Feb 26th
410 CCC, 2015. Power Sector Scenarios for the 5th Carbon Budget.eg Figure 2
411 Good Energy, 2015. Wind and solar reducing consumer bills.
412 Jacobson MZ, Howarth RW, Delucchi MA, et al. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight. *Energy Policy*. 2013;57:585–601
413 Jacobson MZ, Delucch MA, Ingraffea AR, et al. A roadmap for repowering California for all purposes with wind, water, and sunlight. *Energy*. 2014;73:875–889.
414 Department of Energy and Climate Change. (2014c). UK Energy in Brief 2014. [Online] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/350941/UK_Energy_in_Brief_2014_revised.pdf
415 Department of Energy and Climate Change. (2014d). UK Energy Statistics. [Online] Available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296183/pn_march_14.pdf
416 Department of Energy and Climate Change. (2014c). UK Energy in Brief 2014. [Online] Available at:

471. According to estimates of recoverable shale gas reserves, SGP could help eliminate the UK's reliance on gas imports. However, this would require a large onshore gas industry. Bloomberg New Energy Finance estimated in 2013 that eliminating imports would require the drilling of around 10,000 wells over a 15-year period, based on optimistic assumptions for flow rates. A lower flow rate might mean up to 20,000 wells, draining an area twice the size of Lancashire.[417]

Carbon Capture and Storage (CCS)

472. CCS refers to a process involving three main steps: 1) the separation of CO_2 from a gas stream; 2) CO_2 compression and transport (via pipeline or shipping); and 3) CO_2 storage in a suitable geological site (e.g. saline aquifers and depleted oil and gas reservoirs).

473. CCS technologies are categorised according to the class of capture process (post-combustion, pre-combustion, and oxy-combustion) and type of separation technology (absorption, adsorption, membranes, cryogenic distillation, gas hydrates, and chemical looping).[418]



(Source: Budinis, Krevor, MacDowell et al, 2016. Can Technology unlock 'unburnable' carbon? London: Sustainable Gas Institute).

474. Post-combustion capture involves the separation of CO_2 from a flue stream after a fossil fuel has been combusted. Pre-combustion CCS separates CO_2 from a hydrogen-rich gas called syngas prior to combustion. The syngas is obtained by gasification of a fuel. Oxy-combustion capture is characterised by the combustion of a fossil fuel with enriched oxygen which generates a flue

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https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/350941/UK_Energy_in_Brief_2014_revised.pdf

[417] Bloomberg New Energy Finance, 2013. UK shale gas no "get out of jail free card". Feb 21st

[418] Budinis, Krevor, MacDowell et al, 2016. Can Technology unlock 'unburnable' carbon? London: Sustainable Gas Institute.

stream without impurities, where CO_2 can be separated more easily by condensing the water vapour.

475. CCS can also be combined with Negative Emission Technologies (NETs) such as reforestation, afforestation, agricultural soil carbon storage, biochar and bioenergy with carbon capture and storage (BECCS). BECCS technologies which combine biomass with CCS can be deployed for processes in the bio-refining sector, biofuel sector, power and heat sector, and in industrial processes for the cement, steel and paper sector.

476. The *technical potential* of NETs has been estimated to be 120 $GtCO_2$ until 2050. This would represent an extension of the 2050 carbon budget by 11–13% for a 50–80% probability of remaining below a 2°C temperature increase.[419] Another higher end projection of the future potential of BECCS sees negative GHG emissions being generated by up to 10.4 $GtCO_2e$/yr by 2050.[420]

477. A key issue about CCS and BECCS is the extent to which it is viable and affordable, and the speed at which it can be deployed in light of the shrinking carbon budget available.

478. The International Energy Alliance (IEA) which considers CCS a key option for mitigating CO_2 emissions, highlights the uncertainty of its pace of deployment and concludes that its effect before 2050 is likely to be modest.[421] A proposed IEA roadmap to assist governments and industry to integrate CCS into their emissions reduction strategies suggests CCS being able to store a total cumulative mass of approximately 120 $GtCO_2$ between 2015 and 2050. This is equivalent to about 3.5$GtCO_2$/yr (which is less than 10% of the current annual amount of CO_2e emissions).

479. Questioning the validity of many projections about the future of CCS and BECCS is important given the vast and powerful vested interests involved in maintaining and prolonging the role of fossil fuels in energy systems worldwide.

480. Key barriers to the uptake up of CCS are cost, energy penalty, and location as well as capacity of storage sites.[422] Several barriers are non-technical, including:

- Lack of market mechanism/incentive
- Few effective mechanisms to penalise major CO_2 emitting sources
- Inadequate legal framework allowing transport and storage (both inland and offshore)

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[419] Caldecott, B., et al. (2015). Stranded Carbon Assets and Negative Emissions Technologies. Available online: www.smithschool.ox.ac.uk/research-programmes/stranded-assets/Stranded%20Carbon%20Assets%20and%20NETs%20-%2006.02.15.pdf

[420] Koornneef, J., et al. (2012). Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. *International Journal of Greenhouse Gas Control*, 11, 117–132.

[421] IEA (2013). Technology Roadmap: Carbon Capture and Storage 2013. Online. Available online: www.iea.org/publications/freepublications/publication/technology-roadmap-carbon-captureand-storage-2013.html

[422] Global CCS Institute (2014). Summary report. http://hub.globalccsinstitute.com/sites/default/files/publications/180928/global-statusccs-2014-summary.pdf

- Public awareness and perception.

481. Major potential supply chain constraints include hydrogen turbines for the capture step, pipelines for the transport step, geo-engineers and drilling rigs for the storage step as well as a shortage of petroleum engineers across the full CCS chain.[423] Private investment in CCS is hampered by various risks including technology and construction issues, high up-front capital costs, infrastructure barriers, and operating costs (also affected by a fuel price risk).

482. According to the Global CCS Institute, one major barrier to CCS in the power industry is the high capital cost and 'energy penalty' compared to traditional fossil fuel fired generators. At the moment, a plant with CCS is more expensive (in terms of capital and operating costs) than the same plant without CCS.

483. Reports of the cost of CCS show a great variability, with a lack of data for specific processes or capture technologies. The capture step is the most expensive step of the CCS chain, with a cost of carbon equivalent to 20–110 \$2015/tCO_2. Transport cost ranges between 1.3 and 15.1 \$2015/tCO_2/250km, depending on the location and length of the pipeline. Storage cost depends on the type of storage site and the possible reuse of existing facilities and is between 1.6 and 31.4 \$2015/tCO_2.[424]

484. Budinis et al hypothesise that the constraint on CCS is not cost related or supply chain related (particularly in later years) but that CCS is not adequately effective in reducing residual emissions to make it a favourable option in climate change mitigation scenarios. Developers have so far focussed on 85–90% capture rates which would not be sufficient with tighter global emission limits. However, higher capture rates from 2050 onwards (even greater than 95%) may lead to natural gas becoming viable again as a safe fossil fuel.

485. Factors determining the feasibility of location and capacity of storage sites include: a) cumulative capacity of carbon storage; b) rates of release and uptake; c) connection from source to store; and d) climate impact of storage timescale.

486. Global geo-storage capacity is believed to be larger than the CO_2 embodied in present-day fossil fuel reserves.[425] However, reservoir pressurisation in saline aquifers will limit the accessible CO_2 geo-storage capacity in the absence of pressure management strategies. The exact fraction of available space has complex dependencies on reservoir, rock, and fluid properties.

487. It is estimated 1,000 Gt of storage capacity is available in oil and gas (hydrocarbon) reservoirs alone which would mean little in the way of storage capacity limits affecting the first generation of commercial CCS deployment in scenarios involving less than 500 Gt of CO_2.

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[423] IEAGHG (2012). *Barriers to implementation of CCS: capacity constraints*, Report IEAGHG 2012/09.
[424] Budinis, Krevor, MacDowell et al, 2016. Can Technology unlock 'unburnable' carbon? London: Sustainable Gas Institute
[425] IEAGHG (2016). *Can carbon capture and storage unlock 'unburnable carbon'?*, Report IEAGHG 2016/05.

488. A study of sources and sinks shows that CCS will not be constrained by *local* availability of storage resources in North America, Europe and Brazil. Outside these areas, storage availability is uncertain, although the global distribution of sedimentary basins is such that it is possible that there will be few locations where local storage availability will be a limiting factor.[426]

489. Technology Readiness Levels (TRLs) is a metric used to assess the stage of development of new technologies. TRLs range from 1 to 9, where TRL1 means "basic principles observed and reported" and TRL 9 means "actual system flight proven through successful mission operations". According to one study, post-combustion capture processes lie between TRL 1 and TRL 5 (due to the early stages of technology development for this capture process); pre-combustion capture processes are "likely (to be) decades away from commercial reality"; and oxy-combustion processes are "at the early stages of development", without a clear possibility to understand its future development.[427]

490. While post-combustion and pre-combustion capture technologies are widely used, at the moment there is only one full-scale installation of a coal-power plant, the Boundary Dam Carbon Capture Project.[428] According to the Global CCS Institute, there are currently 55 large-scale CCS projects worldwide in either 'identify', 'evaluate', 'define', 'execute' or 'operate' stage. However, the total number has reduced from 75 (2012) to 65 (2013) to 55 currently (2014).[429]

491. Policy options to increase the deployment of CCS include: carbon trading or taxation; targeted investment support; feed-in schemes which guarantee a fixed fee; a guaranteed carbon price for CCS; and minimum standards, such as a CCS obligation for new installations.

492. In the UK, government encouragement of CCS has waned. In 2007, the government launched a competition for demonstrating post-combustion capture of CO_2 on a coal-fired power plant. In 2010, the competition was opened to gas and in 2013, two bidders were announced: the White Rose project (a coal-fired power plant) and the Peterhead project (a full-scale gas CCS project). However, in November 2015, the £1 billion ring-fenced capital budget for the CCS Competition was withdrawn by the government.

493. Although CCS appears important in underpinning any role for fossil fuels in the future, CCS has not been adopted to a great extent. For some people, BECCS and reforestation are attractive

[426] Koelbl BS, et al, 2014. Uncertainty in Carbon Capture and Storage (CCS) deployment projections: a cross-model comparison exercise. *Climatic Change*, 123, 461–476.
[427] Rubin ES et al, 2012. The outlook for improved carbon capture technology. *Progress in Energy and Combustion Science*, 38, 630–671.
[428] Budinis, Krevor, MacDowell et al, 2016. Can Technology unlock 'unburnable' carbon? London: Sustainable Gas Institute
[429] Global CCS Institute (2014). Summary report. http://hub.globalccsinstitute.com/sites/default/files/publications/180928/global-statusccs-2014-summary.pdf

options for creating negative emissions.[430] However, Estimations of NETs potential until 2100 are affected by great uncertainties, especially with regard to the availability and accessibility of geological storage, and are therefore difficult to estimate. They almost certainly do not offer a viable alternative to mitigation in the coming decades.[431]

Energy efficiency and conservation

494. Improving energy efficiency and reducing overall levels of energy consumption are vital components of any plan to mitigate global warming. However, improvements in energy efficiency will have little impact if money 'saved' through energy efficiency is then spent on further energy services. This is a phenomenon referred to as "Jevons' paradox".

495. Most energy services are highly inefficient. For example, cars in the UK street have emissions of over 160gCO_2/km on average, even though there are over 200 model variants of standard-engine cars (i.e. not electric or hybrid) with emissions of under 100gCO_2/km being sold at little to no price premium. Televisions and IT equipment have huge variations in energy consumption for essentially the same level of service. An A rated refrigerator consumes in the region of 80% more energy than an A+++ alternative; again at very little price penalty. A vast amount of the UK housing stock has an Energy Performance Certificate rating of D or below.

496. A Green Alliance report that describes the failure of the UK to harness the potential for saving electricity proposes a strategy to create incentives for companies to benefit from energy efficiency measures by making two changes to the electricity market: a) a 'negawatts feed-in tariff' paid on the basis of avoided energy consumption, with recipients competing in an auction to deliver energy savings in homes and businesses at lowest cost; and b) opening the capacity market to competition from demand-side response and energy demand reduction on an equal basis with electricity generation.[432]

Economics and Political Leadership

Economics

497. The economics of the energy sector is another critical dimension of the debate on shale gas.

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[430] van Vuuren D, et al, 2013. The role of negative CO2 emissions for reaching 2 °C - insights from integrated assessment modelling. *Climatic Change*, 118, 15–27.
[431] McLaren D, 2012. A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection*, 90, 489–500.
[432] Green Alliance, 2015. Getting more from less

498. Crucially, the fossil fuel industry is heavily subsidised.[433] According to the IMF, pre-tax subsidies in the fossil fuel sector have been declining from about 0.7% of global GDP in 2011 to about 0.4% ($333 billion) in 2015. This is still a large subsidy, but dwarfs in comparison to the estimated post-tax subsidy of fossil fuels which was calculated to be about $5.3 trillion (6.5% of global GDP) in 2015. About three-fourths of the post-tax-subsidy is from the externalisation of the costs of air pollution and about a quarter is from the externalisation of costs of global warming.[434]

499. For petroleum, total subsidies were broken down as follows: externalised costs of congestion, accidents and road damage (39%); pre-tax subsidies (17%); global warming (13%), air pollution (18%), and foregone consumption tax revenue (14%). For natural gas, total subsidies were broken down as follows: global warming (53%), pre-tax subsidies (26%), and forgone consumption tax revenue (10%).[435]

500. Energy subsidies for the fossil fuel sector currently damage the environment; cause premature death through local air pollution; exacerbate congestion and other adverse side effects of vehicle use; increase GHG concentrations; impose large fiscal costs on taxpayers; discourage investments in energy efficiency, renewables, and more efficient energy infrastructure; and increase the vulnerability of countries to volatile international energy prices.

501. According to the IMF, the removal of post-tax energy subsidies could reduce premature deaths from local air pollution by more than 50% and generate a substantial fiscal dividend in government revenues, estimated at $2.9 trillion (3.6% of global GDP) in 2015.[436]

502. The Stern Review called the market externality of GHG emissions in the global economy "the greatest and widest-ranging market failure ever seen".[437]

503. Another aspect of market failure in the energy sector it the lack of large-scale 'positive investment' in a clean energy system.

504. For new technologies in the earlier stages, concerted R&D efforts are required.[438] Such efforts may be analogous to the Manhattan Project for nuclear technology, the Apollo Program for space flight, or the Marshall Plan for the post-war reconstruction of Europe. Other climate adaptation measures such as flood protection defences which are capital-intensive investments with uncertain returns, also require public investment.

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[433] Victor, D. The politics of fossil-fuel subsidies: global subsidies initiative & the international institute for sustainable development. Global Subsidies Initiative, International Institute for Sustainable Development, Geneva; 2009

[434] Coady D, Parry I, Sears L and Shang B, 2015. How Large Are Global Energy Subsidies? Washington DC: IMF.

[435] Coady D, Parry I, Sears L and Shang B, 2015. How Large Are Global Energy Subsidies? Washington DC: IMF.

[436] Coady D, Parry I, Sears L and Shang B, 2015. How Large Are Global Energy Subsidies? Washington DC: IMF.

[437] Stern, N. Stern Review on the economics of climate change. HM Treasury, London; 2006

[438] Mazzucato, M. The entrepreneurial state: debunking public *vs* private sector myths. Anthem Press, London; 2013

505. The IEA estimated that to have an 80% chance of remaining on a 2°C stabilisation pathway, *additional* cumulative investment of $36 trillion is required by 2050, roughly $1 trillion per year (in the order of 1% GDP under moderate growth assumptions), with low-carbon technologies and energy efficiency accounting for around 90% of energy system investment by 2035 (currently, this value is around 23%).[439] Another estimate has suggested a lower value of $270 billion per year. [440]

506. In 2013, only 0·1% of institutional investor assets (excluding sovereign wealth funds) were in low-carbon energy infrastructure projects ($75 billion).[441]

507. There are many policy options for available for correcting market failures in the energy sector. Taxes on energy products (such as transport fuels) could be realigned to reflect their carbon content. Carbon pricing that internalises the costs of social and environmental damage may also be achieved through a well designed and equitable cap-and-trade emissions trading systems (ETS).

508. By increasing the burden of taxation on environmentally damaging activities and reducing it on desired inputs, such as labour, an increase in energy prices can be neutralised from a macroeconomic perspective. Although fossil-fuel subsidies and the presence of externalities tend disproportionately to benefit the wealthiest in society (in both national and international contexts), the introduction of carbon pricing and the removal of fossil fuel subsidies may be regressive, as the poorest in society spend a greater proportion of their disposable income on energy. Additional fiscal interventions will therefore be required to protect low-income or vulnerable households.

509. Corrective taxation that internalises CO_2 emissions, air pollution, and transport-related externalities (such as congestion and accidental injury) arising from fossil fuel could also raise additional revenues of 2·6% GDP globally, whilst simultaneously reducing CO_2 emissions by 23% and pollution-related mortality by 63%.[442]

510. Additionally, feed-in tariffs (FiTs), used in the electricity sector to provide a guaranteed rate of return to low-carbon generators, have been shown to be an effective policy instrument that has been responsible for a significant majority of installed global renewable power capacity.

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[439] International Energy Agency. World energy outlook. IEA, Paris; 2012

[440] The New Climate Economy. Better growth, better climate. The Global Commission on the Economy and Climate, New York; 2014

[441] Kaminker, C, Kawanishi, O, Stewart, F, Caldecott, B, and Howarth, N. Institutional investors and green infrastructure investments: selected case studies. Organization for Economic Co-operation and Development, Paris; 2013

[442] Parry, IWH, Heine, D, and Lis, E. Getting the prices right: from principle to practice. International Monetary Fund, Washington, DC; 2014

511. Other interventions to correct market failure in the energy sector include demand-side regulation such as mandatory energy efficiency standards. Examples include a cap on CO_2 emissions from passenger cars per kilometre driven, or on the annual energy consumption of a new building per unit of floor area. Technology standards can also be employed to proscribe the use of certain components in products, or prevent the sale of the least efficient models of a product type.

512. The global pattern of heavy subsidisation of fossil fuel and under-investment in clean energy is apparent in the UK. National subsidies to fossil fuel production have been estimated at an annual average of $9 billion in 2013 and 201 4.[443] In the 2015 Budget, Chancellor George Osborne awarded a further £1.3b in subsidies to the oil industry.[444]This makes the UK one of the few G20 countries that is *increasing* its fossil fuel subsidies.

513. At the same time, the UK is cutting back on renewable energy investments, whilst implementing tax reforms that would make renewable energy companies pay more tax. As noted earlier, the government removed support from solar power in 2015 (causing the loss of up to 18,700 jobs).[445]

514. The large subsidisation of fossil fuel continues despite the government agreeing with the IPCC and other international bodies that the removal of subsidies from the fossil fuel industry is important. At the 2014 climate summit in New York, David Cameron himself described fossil fuel subsidies as “economically and environmentally perverse", as they “distort free markets and rip off taxpayers”.[446]

515. At the same time, oil companies in the UK North Sea that have made vast profits (33% rate of return) from 2008 and 2014 have paid relatively little in the way of tax. According to Platform, the UK takes a lower share of revenue from its oil resources than most other countries. On average, governments receive 72% of net revenue from oil production, compared to 50% from most UK fields. Norway, operating in the same fields in the North Sea, takes 78%.[447]

Political leadership

516. Transforming the global economy within the required timescale demands unprecedented action in both industrialised and developing countries. According to the Lancet-UCL Commission, industrialised countries need to embark immediately on CO_2 reduction programmes “with a high level of ambition”. Put another way, transition to a low-carbon energy infrastructure implies a

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443 Bast E, Doukas A, Pickard S, van der Burg L and Whitley S, 2015. Empty promises: G20 subsidies to oil, gas and coal production. London: Overseas Development Institute and and Oil Change International.
444 See here: http://platformlondon.org/wp-content/uploads/2016/03/NorthSea_Oil_Tax_Facts.pdf
445 Calculations show that industries like wind, wave and tidal and could employ 40,000 more North Sea workers than the existing fossil economy.
446 See here: http://blueandgreentomorrow.com/2014/09/24/un-climate-summit-cameron-calls-for-ending-fossil-fuel-subsidies-and-a-strong-climate-deal-in-paris/
447 See here: http://platformlondon.org/wp-content/uploads/2016/03/NorthSea_Oil_Tax_Facts.pdf

radical transformation of not just the energy sector, but the behaviours and consumption patterns that feed off our burning of fossil fuel.

517. The Lancet-UCL Commission on Climate Change and Health also noted that transition to a low-carbon infrastructure "requires challenging the deeply entrenched use of fossil fuels". Decarbonisation and reducing energy demand is not a simple challenge of cleaning up pollutants or installing new equipment: it requires systemic transformations of energy infrastructures and associated systems.

518. A collective political, policy and scientific failure is exemplified by the recent expansion of coal use across the world that reversed the global pattern through most of the 20th century of shifting towards less carbon intensive and less polluting fossil fuels.

519. The fact that global emissions have risen over the past decade demonstrates a remarkable inability to respond effectively and collectively to the threat of climate change. It also demonstrates that most of our institutions are built around narrow, short-term horizons, and vested interests; and that we are locked into a model of economic growth that is centred around material consumption and tied to fossil fuel.[448]

520. Other reasons why effective action has been prevented include the fact that climate science is complex and unavoidably involves a degree of uncertainty which creates room for equivocation and misunderstanding,[449] and that climate change is psychologically distant in temporal, social and geographic terms for many people which dampens concern and willingness to act.[450]

521. Finally, as noted by the Lancet-UCL Commission, "the active promotion of misinformation, motivated by either ideology or vested economic interests" has hindered effective action.

522. In the past two decades, much of the bold and innovative policy-making to address climate change have been driven at the level of cities, which have created the platform for new advocacy coalitions and even for new cross-border para-diplomatic links (e.g. through Local Governments for Sustainability, the World Mayors Council on Climate Change and the Climate

[448] Unruh, GC. Understanding carbon lock-in. Energy Pol. 2000; 28: 817–830
[449] Hulme, M. Why we disagree about climate change: understanding controversy, inaction and opportunity. Cambridge University Press, Cambridge; 2009
[450] Spence, A, Poortinga, W, and Pidgeon, N. The psychological distance of climate change. Risk Anal. 2012; 32: 957–972

Leadership Group).[451 452, 453 454] These experiences point to the emerging importance of sub-national leaders in global environmental governance.[455]

523. As a wealthy nation with a skilled workforce and a world-leading renewable energy resource base, choosing to develop a new fossil fuel industry would not only threaten to break our national targets to reduce GHG emissions, but also damage the UK's international reputation and undermine the delicate negotiations being undertaken to strengthen international resolve to prevent runaway global warming and climate collapse.

Co Benefits

524. Although the primary reason for decarbonising of our energy system is to mitigate climate change, various important and relevant positive social, ecological and health dividends would arise.

525. Several links between climate mitigation practices and technologies and improved health and wellbeing have been established.[456 457] From a global perspective, crop yields have much to gain from the mitigation of short lived climate pollutants such as methane, black carbon, hydrofluorocarbons, and tropospheric ozone.[458]

526. The health benefits of reduced air pollution in the EU alone (to mitigate climate change) have been valued at €38 billion a year by 2050.[459] Another estimate suggests that a doubling of RE use from 2010 to 2030 could avoid up to $230 billion of external health costs annually by 2030 globally.[460] Similarly, it has been estimated that the health benefits of reducing methane

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[451] Roman, M. Governing from the middle: the C40 Cities Leadership Group. Corp Gov. 2010; 10: 73–84
[452] Bulkeley, H. Betsill. M. Cities and climate change: urban sustainability and global environmental governance. Routledge, New York; 2003
[453] Boutiligier, S. Cities, networks, and global environmental governance. Routledge, London; 2013
[454] Curtis, S. Global Cities and the Transformation of the International System. Rev Int Stud. 2011; 37: 1923–1947
[455] Gordon, DJ. Between local innovation and global impact: cities, networks, and the governance of climate change. Can Foreign Pol J. 2013; 19: 288–307
[456] Proust, K, Newell, B, Brown, H et al. Human health and climate change: leverage points for adaptation in urban environments. Int J Environ Res Public Health. 2012; 9: 2134–2158
[457] Shaw, MR, Overpeck, JT, and Midgley, GF. Cross-chapter box on ecosystem based approaches to adaptation—emerging opportunities. in: CB Field, VR Barros, DJ Dokken, (Eds.) Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA; 2014: 101–103
[458] Scovronick, N, Adair-Rohani, H, Borgford-Parnell, N et al. Reducing global health risks through mitigation of short-lived climate pollutants: scoping report for policymakers. World Health Organization and Climate and Clean Air Coalition, Geneva; 2015
[459] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: a roadmap for moving to a competitive low carbon economy in 2050. European Commission, Brussels; 2011
[460] International Renewable Energy Agency. REmap 2030: a renewable energy roadmap. IRENA, Abu Dhabi; 2014

emissions in industrialised nations would exceed the abatement costs even under the least aggressive mitigation scenario.[461]

527. Policies that encourage active travel (eg, walking and cycling) would produce significant reductions in cardiovascular disease, dementia, obesity, diabetes, several cancers, and in the duration and severity of depressive episodes.[462] [463] One study estimates that increased levels of active travel coupled with increased fuel efficiency in the UK's urban areas could lead to a cumulative net saving to public funds of more than £15 billion by 2030, whilst achieving GHG reductions of over 15% in the private transport sector.[464]

528. In the UK, retrofits aimed at improving the energy performance of houses have the potential to offer substantial health benefit provided adequate ventilation to control indoor pollutants is installed. Increased energy efficiency will also help reduce fuel poverty, excess winter mortality rates, and respiratory illness rates in children.[465] Nicol and colleagues estimated that improved housing in England alone could save the NHS more than €700 million per year in treatment no longer required.[466]

529. According to Copenhagen Economics, improvements in housing energy efficiency in Europe would produce both energy and healthcare savings, and reduce public subsidies for energy consumption by €9–12 billion per year.[467] A modelling study by Hamilton et al. assesses the potential health benefits of 5.3m loft insulations, 6.5m solid wall insulations, 5.7m cavity wall insulations, 2.4m double-glazing installations, 10.7m high-efficiency condensing boiler installations and several ventilation system installations.[468]

530. Clearly, there are also potential risks from decarbonisation and the use of policies and technologies aimed at reducing energy consumption. These include erratic and inadequate

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[461] West, J, Fiore, A, and Horowitz, L. Scenarios of methane emission reductions to 2030: abatement costs and co-benefits to ozone air quality and human mortality. Clim Change. 2012; 114: 441–461

[462] Woodcock, J, Edwards, P, Tonne, C et al. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. Lancet. 2009; 374: 1930–1943

[463] Patz, JA, Frumkin, H, Holloway, T, Vimont, DJ, and Haines, A. Climate change: challenges and opportunities for global health. JAMA. 2014; 312: 1565–1580

[464] Jensen, HT, Keogh-Brown, MR, Smith, RD et al. The importance of health co-benefits in macroeconomic assessments of UK greenhouse gas emission reduction strategies. Clim Change. 2013; 121: 223–237

[465] Liddell, C and Morris, C. Fuel poverty and human health: A review of recent evidence. Energy Pol. 2010; 38: 2987–2997

[466] Nicol, S, Roys, M, Davidson, M, Ormandy, D, and Ambrose, P. Quantifying the economic cost of unhealthy housing—a case study from England. in: M Braubach, DE Jacobs, D Ormandy (Eds.) Environmental burden of disease associated with inadequate housing: a method guide to the quantification of health effects of selected housing risks in the WHO European Region. World Health Organization Regional Office for Europe, Copenhagen; 2011: 197–208

[467] Copenhagen Economics. Multiple benefits of investing in energy efficient renovation of buildings: impact on public finances. Renovate Europe, Copenhagen; 2012

[468] Hamilton IG, Milner J, Chalabi Z, et al. The health effects of home energy efficiency interventions in England: a modelling study. BMJ Open 2014; 5 (4).

energy supplies and unintended consequences such as sub-standard housing ventilation caused by poorly designed home insulation improvements.[469]

531. The economic effects of a transition to a decarbonised energy and economic system will be substantial. Whilst employment in fossil fuel-related and emission-intensive industries would decline over time, low-carbon technology industries would expand and increase employment. IRENA estimate a net global increase of 900 000 jobs in core activities alone (i.e. not including supply chain activities) if the level of renewable energy in global final energy consumption doubles from 18% in 2010 to 36% of by 2030.[470]

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469 Davies, M and Oreszczyn, T. The unintended consequences of decarbonising the built environment: a UK case study. Energy Build. 2012; 46: 80–85

470 International Renewable Energy Agency. REmap 2030: a renewable energy roadmap. IRENA, Abu Dhabi; 2014