

A review of the public health impacts of unconventional natural gas development

P. J. Saunders · D. McCoy · R. Goldstein · A. T. Saunders ·
A. Munroe

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Abstract The public health impact of hydraulic fracturing remains a high profile and controversial issue. While there has been a recent surge of published papers, it remains an under-researched area despite being possibly the most substantive change in energy production since the advent of the fossil fuel economy. We review the evidence of effects in five public health domains with a particular focus on the UK: exposure, health, socio-economic, climate change and seismicity. While the latter would seem not to be of significance for the UK, we conclude that serious gaps in our understanding of the other potential impacts persist together with some concerning signals in the literature and legitimate uncertainties derived from first principles. There is a fundamental requirement for high-quality epidemiological research

incorporating real exposure measures, improved understanding of methane leakage throughout the process, and a rigorous analysis of the UK social and economic impacts. In the absence of such intelligence, we consider it prudent to incentivise further research and delay any proposed developments in the UK. Recognising the political realities of the planning and permitting process, we make a series of recommendations to protect public health in the event of hydraulic fracturing being approved in the UK.

Keywords Hydraulic fracturing · Fracking · Shale gas · Public health

Introduction

Unconventional natural gas development utilising the hydraulic fracturing of shale formations to extract natural gas (commonly known as ‘fracking’) continues to command a high public, political and media profile, especially in the light of recent planning decisions in the UK and elsewhere. It remains a controversial process with proponents arguing that it will safely provide cheap, secure and clean energy, local employment and economic development while opponents are sceptical about such claims and remain concerned about potential health, environmental, social and economic damage associated with the development, operation and decommissioning of sites and

P. J. Saunders (✉)
University of Staffordshire, Stoke-on-Trent, UK
e-mail: carolan57@icloud.com

D. McCoy
Queen Mary University of London, London, UK

R. Goldstein
West Midlands Public Health Training Scheme,
Birmingham, UK

A. T. Saunders
carolan57 Ltd, Birmingham, UK

A. Munroe
Medact, London, UK

infrastructures. While these issues have been under-researched, and remain so, there has been a surge of peer-reviewed papers and reviews published in recent years with over 80% of the peer-reviewed scientific literature on shale and tight gas development published since 1 January 2013 and over 60% since 1 January 2014 (Hays and Shonkoff 2016). A number of detailed ‘grey literature’ reviews have also been published recently (Task Force on Shale Gas 2015; McCoy and Saunders 2015; Lightowlers 2015; Public Health England 2014; New York State Department of Health 2014; Maryland Institute for Applied Environmental Health School of Public Health 2014; The Royal Society and The Royal Academy of Engineering 2012; AEA Technology 2012), but there is considerable variability in the aspects of public health addressed. This paper attempts to capture, review and interpret the published literature across all the accepted domains of public health in a systematic way and consider specific implications for the UK. This review is comprehensive rather than exhaustive given the rapidly developing literature and challenges in capturing all public health dimensions.

The unconventional natural gas development process

There are several terms and colloquialisms used to describe this process and its various stages in both the media and scientific literature with some being used interchangeably (a glossary of abbreviations and acronyms used in this review is given in Appendix 1). This can cause confusion and the term ‘fracking’ has evolved into a generic description of the whole process rather than simply a contraction of ‘hydraulic fracturing’, a specific well stimulation technique. This is important in assessing public health effects, as there are concerns across the entire unconventional natural gas process and not simply the well stimulation element. Consequently, this review uses the term unconventional natural gas development (UNGD). This refers to natural gas produced from atypical reservoirs such as shale or coal seams and other low permeability formations requiring different techniques from those used for conventional formations which enable exploitation through natural pressure and pumping operations. Most natural gas is extracted from these ‘conventional’ deposits in porous rock such as sandstone. The significant amounts of gas in

‘unconventional’ deposits have become commercially accessible with the development of new technologies and techniques including high-volume hydraulic fracturing (HVHF), directional drilling, chemical engineering processes and intensive clustering of wells. HVHF wells can be drilled vertically for hundreds of metres and then horizontally for up to around 3 km. Small detonations and explosions are used to break up and fracture the rock and the injection of large volumes of pressurised fracturing fluid (a mix of water, particulates and a variety of other chemicals) deep underground to create or reopen cracks or fissures in the shale formation to release the trapped gas. While hydraulic fracturing has been used since the 1940s (Moore et al. 2014), the scale, coverage and intensity of the contemporary industry are of different magnitudes to that of the past. The consolidation of several wells on one well pad and the refracturing of wells to maintain gas flows establish an intense and prolonged level of industrial activity (Adgate et al. 2014). While there is no such thing as a standard UNGD site and each development will vary in terms of capacity, intensity and potential impact, an average fracking episode can inject 2–8 million gallons of fracturing fluid and each well can be hydraulically fractured multiple times during its operational life (New York State Department of Environmental Conservation 2011).

The development, functioning, decommissioning and remediation of UNGD sites are major engineering, logistical and construction projects involving the transport, use, extraction, distribution, storage and disposal of huge quantities of materials and waste, often 24 h a day for several years. The industry is long established and most intensive in the USA, and consequently, most of the published literature is from the US experience. There are major differences in the geology, size, population density and energy economies of the USA and the UK. The process, if approved in the UK, will also be managed and regulated differently. It is important to recognise, for example, that the UK commitment to ensure that UNGD operations will be sited close to mains water supply and the gas distribution network will considerably reduce the number of truck movements compared to the USA. However, many of the fundamentals of UNGD and its consequences will be similar, or broadly so, to those in other developed nations. It is important that administrations considering

introducing or expanding UNGD are informed by the experiences of the most mature, intensive and significant industry.

Review methods

Public health is by its nature a broad concept open to different interpretations and understanding. The UK's Faculty of Public Health (FPH) defines it as 'the science and art of promoting and protecting health and well-being, preventing ill health and prolonging life through the organised efforts of society'. The FPH has further developed this definition by identifying three key domains of health protection, health improvement and service improvement (The UK's Faculty of Public Health 2016). There are also powerful proximal and distal interdependencies between the public health hazards, exposures and potential outcomes associated with UNGD at both temporal and spatial levels. The search terms used in this review and its structure reflect these issues and include conventionally accepted public health metrics and outcomes but also the effects of UNGD on economic activity, social cohesion, geology, and energy policy and security.

An initial scoping search and assessment of recent reviews together with the advice of key researchers, scientists and practitioners in public and environmental health were used to frame detailed search terms. The search strategy is based on five categories of potential impacts of UNGD, viz. exposure, health, socio-economic effects and public health nuisance, climate change, and seismicity.

The following databases were searched through January 2016: Ovid Medline, Economic and Social Research Council, Centre for Economic Policy Research, Physicians, Scientists, and Engineers for Healthy Energy (PSE Healthy Energy) Database on Shale and Tight Gas Development (the most comprehensive UNGD citation database) and Scopus. Appendix 2 gives details of the search strategies and inclusion/exclusion criteria. The grey literature, following advice from recognised experts in the field, was assessed including domestic and international government and key institutional websites. Searches were run independently by two reviewers who assessed titles and abstracts for relevance, and full copies were obtained for inclusion or further

assessment. Reference lists were examined, forwards and backwards, for papers not identified in searches. Reviewers independently applied pre-defined inclusion/exclusion criteria, and unresolved disagreements were referred to the lead author for consideration. Full copies of included papers were randomly allocated to five reviewers, and key details and data recorded in extraction tables. Two reviewers independently assessed a random sample of 10% of papers.

Results

Initial agreement at the screening of titles and abstracts was 93 and 100% following discussion. An initial agreement at the full paper screening stage of 95% increased to 100% following discussion of differences. A summary of the five most common reasons for rejection is given in Table 1.

Figure 1 summarises the results of the search strategies and application of inclusion/exclusion criteria. A total of 156 peer-reviewed papers and reviews have been included: 70 relating to exposure, 34 to climate change, 23 to health, 19 to economic and/or social, and 7 to seismic (nine papers are discussed in two sections and one in three sections), and 14 relevant reviews covering two or more domains were also identified. Appendix 3 provides the included/excluded papers ($n = 175$) and reasons for exclusion. A list of the papers identified and included as meeting the inclusion criteria for each section together with their reported relationship with UNGD is given in Tables 2, 3, 4, 5, 6 and 7. Additional background papers are also used where required for clarity in the text.

Table 1 Summary of five most common reasons for rejection of papers

Reason for rejection	Number
Not UNGD or doesn't identify UNGD component	43
Not peer-reviewed	19
Methodological/experimental	13
Inadequate economic analysis	12
Hypothetical case studies	11

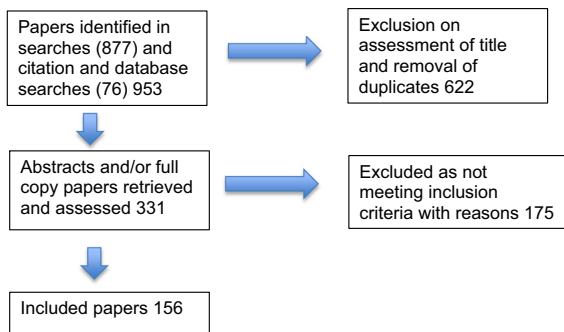


Fig. 1 Review flowchart

Discussion

Exposure pathways

In common with any complex industrial process, UNGD produces a range of chemical hazards (Adgate et al. 2014). While it is important to understand the toxic potential of the chemicals used and produced by the process, it is critical to understand the exposure potential. Without a plausible exposure pathway, these chemicals, no matter how toxic, will remain a *hazard* as opposed to presenting a *risk*. The former requires monitoring, the latter an intervention to prevent exposure or reduce it to a safe level. In addition, the magnitude of any health impact will be influenced by a range of factors including the rate of release of the chemicals, their fate and transport, persistence, human behaviour and the frequency and duration of human exposure (Adgate et al. 2014). A review of the toxicity of 352 chemicals used in US natural gas operations including UNGD found that 25% were potentially mutagenic or carcinogenic (Colborn et al. 2011). In addition, over 75% had the potential to cause effects on the skin, eyes, respiratory and gastrointestinal (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 USA is limited, partly by commercial confidentiality, and some of the chemicals disclosed have not been subjected to a full toxicological assessment. A systematic evaluation of the potential reproductive and developmental toxicity of over 1000 chemicals identified in fracturing fluids and/or wastewater

found that data were available for only 24% of these chemicals, 65% of which suggested potential toxicity (Elliott et al. 2016). An earlier literature review also concluded that chemicals used and produced in unconventional oil and gas operations were known developmental and reproductive toxins (Webb et al. 2014). A study for the German Federal Environment Agency considered that the lack of data on the composition of fluids used together with the chemical and toxicological properties of additives prevented a comprehensive risk assessment (Bergmann et al. 2014). This study found that critical data were either not openly accessible, not yet evaluated, or didn't exist; a gap which requires additional studies and research although it concluded that the process presented plausible exposure hazards. An analysis of fracturing fluids from almost 3000 wells over 4 years identified 347 constituents that could be identified by a Chemical Abstract Service Registration Number (Wattenberg et al. 2015). The paper assessed chronic and acute health hazards associated with those with 25 reports of use. Approximately one-third of the most hazardous were also in the top 30 most commonly used constituents including naphthalene and benzyl chloride. An assessment of the human toxicity potential of UK shale gas production for electricity generation has estimated it to be 3–4 times worse than that of conventional gas, although an order of magnitude better than nuclear, solar or coal power (Stamford and Azapagic 2014).

There is clear evidence of chemical releases from the UNGD process to the most important environmental media in this context, air and water. Jackson et al. (2014) and Shonkoff et al. (2014), for example, have identified the risk of toxic releases to water and air, especially if the process is not managed effectively. These exposure pathways will become more important if UNGD is introduced to new regions and populations or is extended in those regions where already established. It has been noted, for example, that the rapid increase in the technology's development in the USA has brought wells and related infrastructure closer to population centres (Adgate et al. 2014). These impacts can be proximal, e.g. quality of life (Lampe and Stolz 2015), local releases of pollutants such as diesel exhaust, oxides of nitrogen (NO_x), particulate matter (PM) (Moore et al. 2014) and silica from transport and site equipment (Esswein

Table 2 Exposure papers

Paper	Reported impact/ association	Paper	Reported impact/ association	Paper	Reported impact/ association
Ahmadi and John (2015)	Yes	Jackson et al. (2013a, b)	Yes	Thompson et al. (2014)	Yes
Alawattegama et al. (2015)	Yes	Jackson et al. (2013a, b)	Yes	Vengosh et al. (2014)	Potential
Bergmann et al. (2014)	Uncertain	Jenner and Lamadrid (2013)	Potential	Vidic et al. (2013)	Potential
Bunch et al. (2014)	No	Kassotis et al. (2014)	Yes	Wattenberg et al. (2015)	Yes—potential
Casey et al. (2015)	Yes	Kemball-Cook et al. (2010)	Yes	Warner et al. (2012)	Yes
Chalupka (2012)	Yes	Kohl et al. (2014)	No	Warner et al. (2013a)	Potential
Colborn et al. (2011)	Potential	Li and Carlson (2014)	No	Warner et al. (2013b)	No
Colborn et al. (2014)	Yes	Litovitz et al. (2013)	Yes	Webb et al. (2014)	Potential
Darrah et al. (2014)	Yes	Llewellyn et al. (2015)	Yes	Zavala-Araiza et al. (2014)	Potential
Davies et al. (2014)	Yes	Macey et al. (2014)	Yes	Zhang et al. (2015)	Potential
Drollette et al. (2015)	Potential	Moore et al. (2014)	Potential	Zielinska et al. (2014)	Yes
Eapi et al. (2014)	Yes	Molofsky et al. (2013)	No	Ziemkiewicz et al. (2014)	Potential
Elliott et al. (2016)	Potential	Myers (2012)	Potential		
Engelder et al. (2014)	No	Nelson et al. (2015)	No		
Esswein et al. (2013)	Yes	Olmstead et al. (2013)	Yes		
Esswein et al. (2014)	Yes	Osborn et al. (2011)	Yes		
Ethridge et al. (2015)	No	Paulik et al. (2015)	Yes		
Ferrari et al. (2013a)	Yes	Pelak and Sharma (2014)	No		
Field et al. (2015)	Yes	Rahm and Riha (2014)	Potential		
Flewelling and Sharma (2014)	No	Rahm et al. (2015)	Potential		
Flewelling et al. (2013)	No	Reilly et al. (2015)	No		
Fontenot et al. (2013)	Yes	Rich et al. (2014)	Yes		
Gilman et al. (2013)	Yes	Roy et al. (2014)	Potential		
Goetz et al. (2015)	Potential	Rozell and Reaven (2012)	Potential		
Gross et al. (2013)	Yes	Sharma et al. (2015)	No		
Heilweil et al. (2015)	Yes	Siegel et al. (2015, 49)	No		
Hildenbrand et al. (2015)	Potential	Stamford and Azapagic (2014)	Uncertain		
Hladik et al. (2014)	Yes	Swarthout et al. (2013)	Yes		
Ingraffea et al. (2014)	Yes	Swarthout et al. (2015)	Yes		

Table 3 General reviews (peer-reviewed)

Paper	Reported association
Adgate et al. (2014)	Potential (hazards, exposures and health effects)
Allen (2014)	Uncertain (climate change, air pollution)
Beaver (2014)	More research required (environment and health, seismicity, healthcare infrastructure)
Eaton (2013)	Uncertain (environmental, ecological, climate change, economic and regulation)
Finkel and Hays (2013)	Potential (exposure, health, climate change)
Finkel et al. (2015)	Yes (health, exposure, climate change, social justice and seismicity)
Hays and Shonkoff (2016)	Yes (environmental, public health, climate change, economic and seismicity)
Jackson et al. (2014)	Neutral if well managed (economic/social, exposure and climate change)
Lampe and Stolz (2015)	Potential if not effectively regulated (exposure, health, regulation and quality of life)
Mash et al. (2014)	Potential (exposure, health and regulation)
Moore et al. (2014)	Yes (climate change, exposure)
Shonkoff et al. (2014)	Potential (environmental public health)
Sovacool (2014)	Uncertain (economic/social, seismic, climate change)
Werner et al. (2015)	Potential (health, exposure, regulation and societal)

Table 4 Health papers

Paper	Reported adverse association
Bamberger and Oswald (2012)	Yes
Bamberger and Oswald (2015)	Uncertain
Bloomdahl et al. (2014)	No
Bunch et al. (2014)	No
Casey et al. (2016)	Yes
Esswein et al. (2013)	Yes
Esswein et al. (2014)	Yes
Ethridge et al. (2015)	No
Ferrar et al. (2013b)	Yes
Fryzek et al. (2013)	No
Jemielita et al. (2015)	Yes
McKenzie et al. (2012)	Yes
McKenzie et al. (2014)	Yes
Paulik et al. (2015)	Yes
Rabinowitz et al. (2015)	Yes
Rosenman (2014)	Yes
Saberi et al. (2014)	Yes
Stacy et al. (2015)	Yes
Stamford and Azapagic (2014)	Better than coal/renewables, worse than conventional gas
Steinzor et al. (2013)	Yes
Swarthout et al. (2015)	No
Witter et al. (2013)	Yes
Zhang et al. (2015)	No

et al. 2013; Chalupka 2012), and the release of fracturing fluids and wastes through spills, leaks or accidents (Rahm and Riha 2014; Ingraffea et al. 2014; Davies et al. 2014; Ziemkiewicz et al. 2014; Jackson et al. 2013b). In the latter context, it is worth noting that anywhere between 9 and 80% of the contaminated fracking fluid (most estimates around 35%) could resurface following a fracking episode (Shonkoff et al. 2014). It is also accepted that some of the formations now accessible to unconventional drilling activities contain significant concentrations of Naturally Occurring Radioactive Materials (NORM) and therefore there is potential for their contamination of environmental media. Regional issues include water quality (Adgate et al. 2014), volatile organic compounds (VOCs), PM, NO_x (Allen 2014) and ground-level ozone (Moore et al. 2014). Indeed, UNGD's photochemical oxidant formation 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; the worst of the other technologies considered (Stamford and Azapagic 2014).

However, despite the potential for environmental and human exposures, any risks associated with UNGD also need to be considered against the environmental health benefits such as substitution of the gas produced for more polluting and water-intensive fuel stocks such as coal. This is discussed further in the climate change section.

Table 5 Economic/social papers

Paper	Reported negative impact
Abramzon et al. (2014)	Yes
Aguilera et al. (2014)	No
Barth (2013)	Uncertain
Bernstein et al. (2013)	Residents willing to pay \$10.50 a month to protect watersheds
Finkel et al. (2013)	Yes
Haefele and Morton (2009)	Yes
Jones et al. (2014a)	Potential
Jones et al. (2014b)	Potential
Kinnaman (2011)	Benefits exaggerated
Lave and Lutz (2014)	Largely negative
Muehlenbachs et al. (2015)	Negative for property values with groundwater supply
Munasib and Rickman (2015)	Some positive effects offset by local negative impacts
Paredes et al. (2015)	Negligible local benefit
Popkin et al. (2013)	Yes
Throupe et al. (2013)	Yes
Weber et al. (2014)	Mostly negative although some positive reports
Weber (2012)	No
Witter et al. (2013)	Yes
Wrenn et al. (2015)	No

Air

A mobile laboratory was used to assess air samples from specifically targeted sites associated with shale gas extraction and distribution as well as during transit through areas of high UNGD activity in NE and SW Pennsylvania (Goetz et al. 2015). This included over 50 compressor stations and over 4200 wells. Samples were taken during August and September 2012 and analysed for a range of gas-phase species and PM. While submicrometre particle mass results were reported as not being elevated, the analyses did not monitor for particle numbers, considered a more important metric in relation to some health impacts (Seaton et al. 1995). While methanol was detected at one compressor station, levels of light aromatic compounds such as benzene or toluene were unremarkable. The latter result is to be expected given that the Marcellus play does not contain oil deposits. The authors recognise that this is a small sample and the results are not generalisable.

Current understanding of local and regional air quality impacts of the five stages of the natural gas life cycle, viz. pre-production; production; transmission, storage and distribution; end use; and well production end-of-life, was considered by Moore

et al. (2014). This review identified clear potential for exposure to hazardous air pollutants (HAPs) from the use of large diesel powered equipment, truck traffic, diesel and gas powered engines for drilling rigs and pumps, volatilisation of components of fracturing fluid including flowback fluids, proppant injection, and venting and flaring. Chemicals include PM, NO_x, methane (covered in more detail in the climate change section) and non-methane volatile organic compounds, respirable silica, hydrogen sulphide (H₂S), sulphur dioxide (SO₂) and formaldehyde although the authors recognise the potential for reduced emissions of carbon dioxide (CO₂), SO₂, NO_x and mercury if natural gas replaced the use of coal or oil. The paper also recognises the lack of monitoring data stating that 'A full classification of all emissions during drilling and hydraulic fracturing does not to our knowledge exist'. They were concerned about the reliance of regulators on generic emission inventories which are based on limited, incomplete and outdated data to assess the air quality impacts of natural gas systems. The lack of data and intelligence on chemicals used and produced was noted, and the paper calls for more research, monitoring, source apportionment and the establishment of an inventory of abandoned wells.

Table 6 Climate change papers

Paper	Reported adverse climate change effects
Allen et al. (2013)	Uncertain
Brandt et al. (2014)	No
Burnham et al. (2012)	Uncertain
Caulton et al. (2014)	Yes
Dale et al. (2013)	Yes—insufficient to meet CC goals
Goetz et al. (2015)	Yes—in exposure as well
Heath et al. (2014)	Uncertain
Howarth et al. (2011)	Yes
Howarth (2014)	Yes
Hultman et al. (2011)	Potential
Jacoby and O’Sullivan (2012)	Uncertain
Jiang et al. (2011)	Potential
Jenner and Lamadrid (2013)	No
Lan et al. (2015)	Yes
Laurenzi and Jersey (2013)	Yes—positive
McLeod et al. (2014)	Potential
McJeon et al. (2014)	Does not change GHG trajectory
Newell and Raimi (2014)	Uncertain
Omara et al. (2016)	Potential
O’Sullivan and Paltsev (2012)	No
Peischl et al. (2015)	Potential
Pétron et al. (2014)	Potential
Schneising et al. (2014)	Yes
Schrag (2012)	Potentially no
Shahriar et al. (2014)	Lower impact than reported elsewhere
Stamford and Azapagic (2014)	Uncertain
Stephenson et al. (2011)	Potential
Tyner and Johnson (2014)	Uncertain
Vinciguerra et al. (2015)	Yes—negative
Wang et al. (2011)	No
Weber and Clavin (2012)	Uncertain
Weyant et al. (2016)	No
Zavala-Araiza et al. (2015a)	Potential
Zavala-Araiza et al. (2015b)	Uncertain

A number of studies, some of which have used source apportionment, have found hazardous airborne levels of VOCs, including polycyclic aromatic hydrocarbons (PAHs), in the vicinity of UNGD sites. The regional impact of UNGD on VOCs was assessed using air samples from across an 8050 km² region surrounding Pittsburgh and data from a mobile laboratory deployed at two sites, one with nearly 300 unconventional natural gas wells within 10 km and a remote location with a single well within 10 km

(Swarthout et al. 2015). The VOC emissions from UNGD operations suggested that natural gas emissions could compromise meeting federal ozone standards, particularly in urban areas.

The Texas Commission on Environmental Quality (TCEQ) has undertaken extensive monitoring of airborne VOCs and a human health risk assessment in the Barnett Shale region (Ethridge et al. 2015). TCEQ developed an extensive inventory of emission sources including information on location, type and

Table 7 Seismicity papers

Paper	Reported association
Baisch (2013) (a peer-reviewed conference proceeding included as direct relevance to UK)	Negligible
Davies et al. (2013)	Negligible
Holland (2013)	Plausible
Kim (2013)	Plausible
van der Elst et al. (2013)	Modest plausibility
Wang et al. (2016)	Plausible
Westaway and Younger (2014)	Negligible

number of emission sources; equipment and activities conducted; releases to air; and proximity of receptors. A helicopter-mounted passive infrared camera was used to identify unreported VOC emission sources. A range of monitoring techniques was used to estimate long- and short-term exposures in areas with and without UNGD during 2009 and 2010 including mobile sampling teams and fixed VOC monitors. While several short-term samples exceeded odour-based air monitoring comparison values (AMCVs) and levels above typical background downwind of UNGD were detected, only three exceeded health-based AMCVs. Short-term sampling found elevated levels of VOCs, most notably benzene, being emitted from a small percentage of those facilities. All long-term VOC levels were below long-term health-based AMCVs. Data from the TCEQ monitoring network for the period 2000–2011 were also reviewed to identify whether UNGD activities were increasing community exposures to VOCs in the Barnett Shale region (Bunch et al. 2014). Comparison with health-based standards found no exceedences of any acute standards although one exceedence of the chronic standard was identified. The latter was not considered to be associated with UNGD activities. The study, supported by an industry representative 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.

Levels of 62 PAHs at 23 residential properties in Carroll County, Ohio, between 0.04 and 3.2 miles of an active well pad in early 2014 were assessed using passive air samplers (Paulik et al. 2015). 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 potentially confounding sources for 3–4 weeks. Levels of total PAHs were an order of magnitude higher than results previously published for rural areas. Stratifying results by distance from active pad zones into ‘close’ (<0.1 mile from an active well), ‘middle’ (0.1–1.0 mile) and ‘far’ (>1.0 mile) found a clear pattern of increasing PAH levels with proximity to well pads. Using benzo[a]pyrene and phenanthrene as representative PAHs associated with cancer and respiratory outcomes found a similar pattern albeit weaker for the latter.

A local impact on levels of methane and H₂S was identified in an analysis of samples taken from around the perimeter of UNGD sites (Eapi et al. 2014). The study involved measuring levels at the perimeter fences of almost 4800 sites in four counties of the Barnett Shale Forth Worth Basin, an area which had experienced an enormous expansion of the industry from 726 wells to nearly 16,000 in the decade following 2001. 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 H₂S. Elevated levels of methane and/or H₂S were found at 21% of sites (high methane levels at 16.5% of sites and high H₂S 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. The authors recognise the importance of distinguishing the specific source of the methane and sampling from the site itself to improve accuracy and inform a definitive conclusion. Researchers from the Texas Center for Energy and Environmental Resources assessed hourly concentrations of 46 non-methane VOCs from three sites representative of locations in, on the periphery of, and an urban site more distant from, the Barnett Shale (Zavala-Araiza et al. 2014). These data were compared to predicted levels from a dispersion model and an emissions inventory. The dominance of light alkanes in the measured data including ethane, propane and *n*-butane reflected the composition of natural gas production emissions. There was modest

temporal variability in emissions from natural gas largely due to meteorology rather than process-related sources such as well unloadings. Predicted concentrations were up to 40% lower than measured values.

Another assessment of the concentrations of air-borne volatile compounds around UNGD sites subject of local concern used both community questionnaires and grab and passive air samples taken by trained members of those communities across five US states (Macey et al. 2014). Residents used an assessment of local conditions to determine the sites of 35 grab samples supplemented by 41 formaldehyde badges at production facilities and compressor stations. 46% of the former and 34% of the latter exceeded Agency for Toxic Substances and Disease Registry (ATSDR) and/or Environmental Protection Agency (EPA) Integrated Risk Information System (IRIS) standards. High concentrations of benzene, formaldehyde, hexane and H₂S were identified. In two states benzene levels exceeded standards, in some cases, by several orders of magnitude. Samples from three states exceeded the standard for formaldehyde and, in one state, for H₂S. Using the experience of local communities to determine sampling sites certainly has merit, but this study is limited by the small number of samples taken.

UNGD is increasingly being conducted in more urban areas in the USA increasing the populations potentially exposed to air emissions from the process. A collaboration between public health and engineering academics addressed four issues in an exploratory study in six counties of the Dallas/Fort Worth areas: the identity and concentration of chemicals in ambient air samples in residential areas near shale gas wells; whether methane-associated chemicals are the primary products of the process; the relationship between the chemicals present in residential ambient air samples near gas wells; and whether emission signatures are associated with the different phases and operations of the UNGD process (Rich et al. 2014). Ambient air samples were collected using 24-h passive samplers at 39 locations in residential areas within 61 m of a UNGD site from 2008 to 2010. Approximately 20% of the 101 chemicals identified are designated as HAPs by the EPA including 1,3-butadiene, tetrachloroethane and benzene with the latter being identified at 76% of sites. Virtually, all the analyses detected methane with levels in most areas much higher than urban background concentrations and the mean level six times higher. Principal

component analysis, a technique to identify how much individual factors account for the variability in a data set, suggested the use of compressors at sample sites as being the dominant source of many of the chemicals, although it is not possible to entirely eliminate other potential contributing sources. Further studies using larger sample sizes and including shorter duration sampling periods are required to confirm these findings and refine source apportionment. A larger study of the impact of shale gas production on population exposure to air pollutants in the Barnett Shale region used a combination of active well VOC emission characterisation and apportionment, pollutant monitoring in a local residential community, and measurement of the pollutant gradient downwind of a gas well (Zielinska et al. 2014). The residential community was located in an area of high well density and comprised 250–300 occupied houses adjacent to, and screened from, a compressor station. There are also numerous production wells in the surrounding area. Monitoring included NO_x, NO₂, SO₂, C₅–C₉ hydrocarbons, carbon disulphide (CS₂) and carbonyl compounds, PM_{2.5} and PAHs. Several samples from wellhead condensate tank venting emissions were used to establish a source profile of a major source of VOC emissions in the study area. Average VOC and PM_{2.5} concentrations in the residential area were generally low, below the National Ambient Air Quality Standard, uniformly distributed, and levels fell to near background at 100 m from the condensate tank. However, source apportionment suggested that gas production was significantly contributing to regional VOCs, an impact considered to be potentially associated with increased UNGD-related diesel vehicle movements.

In one of the few studies examining air quality before, during and after the development and operation of a hydraulically fractured gas well pad, levels of VOCs and carbonyls were measured using a monitoring station 1.1 km from the site in Western Colorado over the course of a year (Colborn et al. 2014). Of the range of VOCs monitored, four were detected in every sample: methane, ethane, propane and toluene. The highest average levels were for methane, methylene chloride, ethane, methanol, ethanol, acetone and propane. The carbonyls formaldehyde and acetaldehyde were also detected in every sample. Very low levels of chemicals associated with urban traffic emissions as opposed to gas operations such as ethane were found. There was considerable temporal

variability in the number and concentrations of chemicals detected although both metrics for non-methane hydrocarbons (NMHCs) were highest during the initial drilling phase prior to fracturing. These results are noteworthy despite the limitations of a single site study with no comparison to air quality standards as it does present before and after data as advocated by several papers (Moore et al. 2014; Adgate et al. 2014; Nelson et al. 2015; Stamford and Azapagic 2014; Jackson et al. 2014).

A small-scale assessment of ambient NMHC levels in Erie Colorado, an area of rapid HVHF expansion in close proximity to residences and situated in a region designated as a federal ozone non-attainment zone, was conducted March–June 2013 (Thompson et al. 2014). Thirty whole air samples were collected March–June 2013 including sites proximate to seven residences near gas wells (the closest within 105 and 424 m), and two areas for comparison, rural farmland and a town on the edge of the Wattenberg Gas Field. A number of other data sources were accessed for comparison including the Boulder County Air Toxics Study, the Colorado Department of Public Health and Environment, the National Oceanic and Atmospheric Administration, and the Boulder County Air Toxics Study. Samples from residential areas close to wells showed mean mole fractions of the C₂–C₅ alkanes 18–77 higher than the regional background and above levels typically reported in large urban centres. Elevated levels were also reported for the region with the highest from the Greater Wattenberg Gas Field. The authors also expressed concern that some benzene analyses were within the chronic health effect range although benzene, toluene, ethylbenzene and xylene (BTEX) compounds were generally comparable to, or lower than, large urban areas. The authors also note that, despite the introduction of tighter emission standards in 2008, ambient levels of NMHC seemed to have increased although they recognise that the data are not necessarily directly comparable. An earlier larger study of VOC levels in NE Colorado used the outputs of the Boulder Atmospheric Observatory during the winter of 2011 (Swarthout et al. 2013) and reported C₂–C₅ alkane mixing ratios an order of magnitude higher than regional background. The mixing ratios, meteorology and vertical profiling implicated natural gas production activities as the source of the elevated VOCs to the north-east of the observatory.

The Center for Atmospheric Particle Studies developed emission inventory for a region within the

Marcellus Shale was used to estimate emissions of NO_x, VOCs and PM_{2.5} in Pennsylvania, New York and West Virginia for 2009 and 2020 (Roy et al. 2014). Monte Carlo modelling was used to address uncertainty. The analysis suggested Marcellus development will be an important source of regional NO_x and VOCs 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 NO_x emissions would challenge ozone management in rural areas. While the Marcellus Shale was not predicted to contribute significantly to regional PM_{2.5} emissions, it could account for 14% (2–36%) of elemental carbon. Modelling also identified the potential for stricter controls to significantly reduce the NO_x contribution.

A RAND Corporation supported study of levels of VOC, NO_x, PM₁₀, PM_{2.5} and SO₂ emissions and the cost of the environmental and health damages associated with shale gas extraction in Pennsylvania found that, while emissions were a small proportion of the statewide total, NO_x emissions were up to 40 times higher in areas with concentrated shale gas activities than permitted for a single minor source (Litovitz et al. 2013). 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 development 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 and the scale of the industry to be the most important factor.

VOC concentrations measured at an atmospheric research facility located in the Colorado Wattenberg field were compared with the composition of the raw natural gas and ambient levels monitored in two other NE Colorado sites (Gilman et al. 2013). Oil and natural gas-related VOCs were identified at all three sites and were considered to represent a significant source of ozone precursors.

While the impact of a single UNGD site on ozone levels is likely to be negligible, the cumulative effect of many thousands of sites could be significant. The long-term relationship between shale gas development and ozone pollution in the Dallas/Fort Worth region of Texas was conducted through a comprehensive

analysis of historical ozone data and a meteorologically adjusted ozone time series (Ahmadi and John 2015). Shale gas extraction had been confined to the Western half of the region, and this geological boundary enabled a comparative assessment with an adjacent non-shale gas region. In addition, regional air quality had been extensively monitored for over 30 years providing an exceptionally comprehensive and extensive data set. Sixteen Continuous Ambient Monitoring Stations provided a time series of 8-h average ozone concentrations. As the number of wells had significantly increased from 2007, the analysis considered trends during the periods 2000–2006 and from 2007 to 2013. This showed that ozone exceedences in the non-shale gas region decreased compared to the shale gas region. This difference was especially noteworthy during the high ozone season when the maximum reduction rate in exceedences in the non-shale gas region was c. 31% more than the shale gas area. 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.

Unexpectedly high ozone mixing ratios were identified in 2005 in the Upper Green River Basin region of Wyoming. These elevated wintertime episodes subsequently reoccurred and were linked to emissions from oil and natural gas sources. This prompted additional air quality network and meteorological monitoring to better identify the source of these events (Field et al. 2015). This study reported numerous localised ozone episodes during the winter of 2011 whereas none were identified in 2012, a period of significantly lower ambient total NMHCs. Characterisation of the NMHCs revealed a dominance of compounds associated with fugitive emissions of natural gas and condensate. The impact on ozone levels was also studied in response to the increase in UNGD in the Haynesville shale and the potential release of precursors from the process (Kemball-Cook et al. 2010). In the absence of basic peer-reviewed data, the best available production and activity data were accessed and crosschecked. Sources included state agencies, but the authors were unable to obtain data from any of the producers. This intelligence was used to develop projections for future production under three different intensity conditions based on the number of new wells drilled and production estimates

for each new active well. These estimates were used to develop emission inventories for each scenario. Data from a development in a similar nearby formation, the Barnett Shale near Dallas/Fort Worth, were utilised as a surrogate for modelling growth in drilling activity. Estimated emissions of the ozone precursors NO_x, VOCs, and carbon monoxide (CO) were large enough to justify an evaluation of the impact on ozone generation. This suggested that the effects in some areas would threaten achievement of proposed ozone standards even in the model assuming limited UNGD development of these areas. The study evaluated near-term ozone impacts, and projections indicated that emissions could increase through 2020. Drill rigs, compressor stations and gas plants were identified as the principal sources of NO_x, and the authors suggest additional controls on these elements of the process.

Occupational studies can provide valuable data on the risk of community exposures. Huge quantities of hydraulic fracturing sand containing up to 99% silica (Chalupka 2012) are routinely used as a proppant to hold open the cracks and fissures created by UNGD. The use of this ‘frac sand’ creates respirable crystalline silica dust, potentially a serious occupational exposure hazard. Chalupka reported that the National Institute for Occupational Safety and Health (NIOSH) found potentially high occupational exposures and that the Occupational Safety and Health Administration (OSHA) had identified the following principal sources of exposure during the UNGD process—access ports on sand-movers; blender hopper; transfer belts; and on-site vehicle traffic. An assessment of 111 personal breathing zone (PBZ) samples from 11 sites in five US states found silica levels exceeded occupational health criteria at all sites and for some jobs by a factor of 10 or more (Esswein et al. 2013); 84, 69 and 51% of samples exceeded the ACGIH Threshold Limit Value (TLV), the NIOSH REL and the OSHA Permissible Exposure Limit (PEL), respectively. In the case of some sand mover operators, the level exceeded the occupational exposure limit (OEL) by a factor of 20, beyond the capacity of the respiratory protection being used. Several workers whose roles would not require close proximity to primary sources were also exposed above occupational standards. A subsequent occupational study assessed exposure data from six unconventional oil and gas sites in Colorado and Wyoming (Esswein et al. 2014). Full-shift and

short-term PBZ samples were collected from volunteer workers together with urine samples. Ambient air samples from specific workplace areas were taken, typically over a 2-day period. Airborne concentrations of benzene exceeded NIOSH Recommended Exposure Limit (REL) and Short-Term Exposure Limit (STEL) concentrations and the American Conference of Governmental Industrial Hygienists (ACGIH) TLV in some cases. Full-shift PBZ exposures for some flowback work roles met or exceeded the NIOSH REL with time-weighted PBZ benzene concentrations for some roles an order of magnitude greater than others. Although real ambient and occupational measures contribute to the validity of the study and the authors considered their results as representative, they cautioned against generalising to all sites given the small size.

While UNGD has been reported as not representing a potential radon exposure source, at least one study has suggested an association. Casey et al. 2015 analysed a subset of indoor radon data in Pennsylvania, a state known for relatively high indoor concentrations, to evaluate associations with a range of factors including UNGD. The data set included 866,735 sample analyses from 762,725 buildings covering every county in the state during 1989–2013. Almost 7500 unconventional natural gas wells had been drilled in 39 counties during 2005–2013. There were no significant differences in radon levels between counties with high (≥ 100 wells by 2013), low (< 100 wells by 2013) or no Marcellus activity before 2001. Consistently lower radon concentrations were identified in samples from counties with low Marcellus activity compared with those with high or no activity before and after drilling started. High-activity counties had significantly higher basement levels than low- or no activity counties from 2005 through 2013 with evidence of a significant upward trend. In addition, a significant upward trend in basement levels was reported from 2004 to 2012 ($p < 0.001$). A significant association between proximity to UNGD and first-floor summer radon concentration and an association for basement levels suggest a potential pathway. The paper recognises several limitations including limited data for the early years of the study, a lack of information on building construction and use, and meteorology. These limitations preclude establishing a causal link between radon levels and UNGD.

Water

Four potential UNGD-associated contamination routes were identified in a 2014 review: (1) stray gas contamination of shallow aquifers; (2) spills, leaks and/or the disposal of inadequately treated wastewater; (3) the accumulation of toxic and radioactive elements in soil or stream sediments near disposal or spill sites; and (4) the over extraction of water resources (Vengosh et al. 2014). The latter is not expected to be an issue in the UK (see discussion section). This review of published data (through January 2014) found that while direct contamination of water resources by fracturing fluids or the fracturing process was uncertain, 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 engineering, monitoring, management and planning interventions to 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. Conceptual models and simulations have been used to evaluate contaminant pathways from the Marcellus Shale to the surface (Myers 2012), for example, concluded that UNGD can release fluids and contaminants from the shale by overburdening the hydrogeology or through the injected fluid forcing other fluids out. While recognising the uncertainties he suggests that transport times from the shale to the surface could be reduced from geological timescales to a few years. This plausibility was also reported following an innovative analysis of the contamination of a groundwater supply serving several properties (Llewellyn et al. 2015). This study identified a complex mixture of organic compounds consistent with flowback from Marcellus Shale gas wells and considered that stray natural gas and chemicals from the UNGD process were the most plausible sources, compounded by wastewaters from a pit leak. However, the lack of data on the composition of drilling, pit and HVHF fluids prevented confirmation of the

source. Four studies considered structural integrity problems associated with UNGD (Ingraffea et al. 2014; Davies et al. 2014; Ziemkiewicz et al. 2014; Jackson et al. 2013b). Ingraffea examined inspection data from >41,000 oil and gas wells in the USA during 2000–2012 and found that unconventional shale gas wells were six times more likely to have such problems affecting cement and/or casings than conventional wells (6.2% cf 1.0%). Davies et al. examined published data sets from Australia, Austria, Bahrain, Brazil, Canada, the Netherlands, Poland, the UK and the USA on well barrier and well integrity failures supplemented with data from online repositories or national databases to estimate the frequency of such failures. Reporting systems were inconsistent leading to considerable uncertainties in the estimates or whether failures had led to leaks into environmental media. Well barrier or integrity failure ranged from 2 to 75%. Marcellus Shale wells (6.3%) were identified as having been reported for contraventions relating to well barrier or integrity failure between 2005 and 2013. Despite the uncertainties in the data sets, the authors considered that well barrier and integrity failure is an important issue for unconventional gas wells. Concerned about the potential risk of contamination due to defects in the construction and quality control of the geomembrane liners and geosynthetic piping components of flowback pits and waste fluid storage, Ziemkiewicz et al. examined 14 pits and impoundments associated with hydraulic fracture wells. They found widespread problems in the construction and maintenance of pipework and storage pit liners presenting risks of environmental contamination. In the absence of comprehensive data together with highly uncertain parameters, Jackson reviewed the evidence and pathways for the migration of gas, fracking fluids and formation water to shallow aquifers and assessed six US case histories including both unconventional and conventional extraction (Jackson et al. 2013b). Contamination was considered plausible, and important sources were described including uncemented annuli, well venting, casing failures and damaged seals, and abandoned wells. The authors recommended more baseline data and field testing of potential mechanisms.

The potential extent of UNGD contamination of water sources is considerable. A probability bounds analysis of the likelihood of natural gas operations in the Pennsylvania Marcellus Shale contaminating

water, for example, estimated that development of 10% of the region's resource would generate a volume of contaminated water equivalent to thousands of Olympic-sized swimming pools and identified wastewater disposal as the most hazardous phase of the process (Rozell and Reaven 2012). The potential contribution of regulatory contraventions has been examined (Rahm et al. 2015). This examination of UNGD-related contraventions of environmental protection standards in Pennsylvania over 6.5 years included different phases of the shale boom cycle characterised by the authors as 'exploratory' (relatively low activity), 'intensification' (increased activity) and 'infill' (reduced drilling of new wells). This enabled an assessment of levels of UNGD activity on contraventions, and the authors also used contraventions reported in the conventional sector as a comparator. The study consider almost 3300 reported contraventions involving 80 companies and found that the rate of contravention increased dramatically from the exploratory period through the intensification period and then fell by 50% as drilling of new wells declined ('infill' period). The authors considered this fall as being due to a number of factors including improved management, inspection and regulation. The assessment of almost 5300 contraventions reported from the conventional sector revealed a different pattern with contraventions increasing with decreasing drilling activity due to inappropriate site restoration. UNGD contraventions were more likely to concern spillages and solid waste management compared to the conventional sector. The importance of effective regulation to protect watersheds was highlighted in a review of the environmental challenges presented by the potential extension of UNGD in Pennsylvania over the next 20 years (Lampe and Stolz 2015). Spillages have been identified as the cause of most incidents of environmental concern including some significant events with confirmed impacts on local water resources (Rahm and Riha 2014). This review of UNGD concluded that while good policy and practices can reduce some risks substantially, significant uncertainty remains and there is a need for more and longer-term water quality monitoring. Despite the potential for leakages, blowouts and spills one review reported just a single documented case of injected fracking fluid directly contaminating groundwater although the study highlighted the problems of commercial confidentiality and a lack of baseline data

and research (Vidic et al. 2013). Following several large flowback spillages and associated concerns about contamination of groundwater in NE Pennsylvania, water samples from 21 drinking water wells whose owners suspected had been contaminated were analysed (Reilly et al. 2015). Well owners were recruited through local newspapers and social media outlets. Samples were taken during 2012 and 2013 and analysed for major and trace ions. Comparison data on groundwater well chemistry were obtained from the Pennsylvania Geological Survey and the US Geological Survey's reports for 1979–2006. Compositional data on Marcellus Shale flowback data were obtained from operators' mandatory annual chemical analyses reports although only around 5% of these reports were complete. Information on other potential causes of contamination such as animal waste, road salt and septic effluent were collected from various regulatory and academic sources. While the results revealed evidence of contamination by animal waste, septic effluent or road salt, there was no indication of contamination by Marcellus Shale flowback. Industry reported data were used to assess the potential impact of surface oil and/or recovered water spills on groundwater contamination over a year in Weld County, Colorado (Gross et al. 2013). UNGD operators reported 77 spills with potential for contamination. Analyses for BTEX showed exceedences 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 acknowledge that some levels may have been higher at the time of incident. The number of incidents is small in comparison with the 18,000 active wells although the self-reported nature of the data introduces potential for under-ascertainment. The authors conclude that surface spills represent a source of groundwater contamination.

Following reports of groundwater contamination in a south-western Pennsylvania community of 190 households, an assessment of the impact of UNGD activity on well water was undertaken using analysis of the chemical and microbiological quality of the water, community perceptions and the sequencing of UNGD operations and failures (Alawattagama et al. 2015). Drilling began in late 2007 with a major increase in activity during 2010/2011, and the study was conducted from late 2011 to early 2014. A total

of 143 households were questioned about proximity to wells and the quality of their water supply. Fifty-seven samples from 33 wells were analysed for a range of inorganic chemicals, 18 wells were tested for six light hydrocarbons, and total coliforms and *E. coli* were tested for in 26 wells. A total of 143 households responded to the survey with 35% reporting changes in the quality of water; the majority concerning taste and/or smell; and 16% loss of quantity. Chemical analyses showed elevated levels of chloride, iron and manganese with the latter exceeding the MCL in 25 households which the authors considered a serious public health issue. While methane was identified in 78% of samples taken, the levels were low in the great majority of analyses. A review of the regulator's data identified several contraventions including compromised well casings and inadequate plugging that could have caused groundwater contamination. The microbiological analyses were reassuring. The authors acknowledge the challenges in definitively linking the contaminants to UNGD and recommend more effective pre-drilling testing together with long-term monitoring. This is a recurrent theme in the literature.

One of the largest studies of groundwater quality in an actively drilled shale formation associated with unconventional oil and gas extraction (UOG) in the Texas Barnett Shale formation with 550 private water well samples serving residential, agricultural and public water supplies was reported in 2015 (Hildenbrand et al. 2015). The majority of samples (83%) were taken from aquifers above the Barnett Shale formation, an area with over 20,000 UOG wells developed since the early 2000s. Analyses identified multiple VOCs including alcohols, BTEX and several chlorinated compounds. However, the authors were unable to confirm that UOG extraction was the source of contamination and again recommended further groundwater monitoring and analysis in the region.

A number of studies have used chemical signatures to more effectively identify the sources of contamination. Heilweil sampled 15 streams in the Marcellus Shale play and analysed using a combination of hydrocarbon and noble gas measurements with reach mass-balance modelling to estimate thermogenic methane concentrations and fluxes (Heilweil et al. 2015). High concentrations of methane consistent with a non-atmospheric source were found in four of

the 15 streams. The isotopic and noble gas characteristics of the dissolved gas in one stream suggested a local shale source. Modelling indicated a thermogenic methane flux discharging into this stream which would have been consistent with a reported stray gas migration from a nearby well. Kohl used strontium as a marker for produced waters given the relatively specific and distinct isotopic well-water signatures (Kohl et al. 2014). Samples of produced waters were taken from six wells in the Marcellus Shale play and a nearby spring over a period 4 months prior to, and 14 months following, hydraulic fracturing. There was no evidence of migration of Marcellus-derived produced waters or contamination of groundwater although the short sampling period makes definitive conclusions problematic. Drollette 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 (Drollette et al. 2015). Fifty-nine samples were analysed for VOCs and gasoline range organic (GRO) compounds, and 41 samples were also analysed for diesel range organic (DRO) compounds. Organic and inorganic geochemical fingerprinting of inorganic constituents, groundwater residence times and dissolved methane concentrations were used to identify potential sources of any contamination. Trace levels of GRO and DRO compounds were detected in 15 and 26% of groundwater samples, respectively. The highest levels of both were invariably within 1 km of active UNGD operations, and in the case of DRO, these were significantly higher than samples taken beyond 1 km ($p = 0.01$). Trace levels, well below the EPA drinking water MCLs, of VOCs including BTEX compounds were detected in 10% of samples. Regulatory data revealed almost 5800 contraventions had been reported at 1729 UNGD sites in Pennsylvania between 2007 and June 2014. Levels of DRO were significantly elevated in groundwater samples in close proximity to these sites and in samples taken within 2 km compared with further than 2 km ($p = 0.03$ in both cases). These relationships were not found for GRO. Geochemical fingerprinting data found no evidence of upward migration and were consistent with a surface source of organic compounds in the study area such as UNGD sites. Sharma monitored the geochemistry of gas samples from seven vertical Upper Devonian/Lower Mississippian gas wells, two vertical Marcellus Shale gas

wells and produced gas from six horizontal Marcellus Shale wells 2 months before, during and 14 months after the fracturing of the latter (Sharma et al. 2015). The results were used to assess gas migration pathways between the hydraulically fractured formation and protected shallow underground sources of drinking water. The isotopic and molecular compositions of gas from the two producing zones were distinct throughout and 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.

West Virginia University sampled 50 streams in a river basin of an area of West Virginia with a long history of coal mining and a then currently active (2012) UNGD industry with 250 wells (Pelak and Sharma 2014). 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. There was no association between any of the geochemical or isotopic parameters and shale production intensity. The study concludes that there was no significant contamination from deep formation brines through natural faults/fractures, conventional oil and gas wells, or pathways created by shale gas drilling in the region. The authors recognised that this study represents a ‘one-time snapshot’ of water quality and recommended routine monitoring to more effectively assess any impact of shale gas drilling. Noble gas and hydrocarbon tracers were used 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 2012/2013 (Darrach et al. 2014). Eight clusters of fugitive gas contamination with increasing levels of methane were identified. The chemical signature of these clusters suggested the cause to be failures of well integrity. Warner sampled 127 drinking water wells and compared with the composition of flowback water samples from Fayetteville Shale gas wells to assess potential contamination by stray gas or fluid migration associated with drilling and exploration (Warner et al. 2013a). 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.

Fontenot 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) (Fontenot et al. 2013). Levels of several inorganic substances were higher in samples taken within 3 km of active natural gas wells than both those taken more distant and the reference samples. A number of these 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 from active extraction areas. Comparing sample results with 10 years of historical data from 330 private drinking water wells located in the same counties prior to gas activities showed significant increases in the mean concentration, maximum detected concentration and MCL exceedences for arsenic, selenium and strontium. While this study shows elevated concentrations of some toxic chemicals in the Barnett Shale region and postulates that the spatial distribution of these results is consistent with the likelihood of more frequent well disturbances and industrial accidents being associated with active gas extraction, the authors recognise that it was not possible to make a causal link.

The impact of the discharge of treated produced wastewater, including that generated by UNGD, on levels of toxic disinfection by-products (DBP) in a receiving Pennsylvanian river was undertaken during 2012 and 2013 (Hladik et al. 2014). Samples were taken from the outfalls from an oil and gas wastewater treatment plant (WWTP) and a municipal treatment plant that did not accept produced waters. Samples were also taken upstream and downstream of both plants, together with samples from the outfall of three other oil and gas wastewater treatment plants in Pennsylvania and three further plants not accepting produced waters in different states: Colorado, Maryland and Virginia. Samples were analysed for 29 DTPs. The range and levels of DBPs in samples taken from the outfalls of municipal treatment plant not accepting produced waters were characteristic of those reported from elsewhere in the USA. The DBP profile at the oil and gas WWTP was very different with relatively high levels of dibromochloronitromethane identified. These samples also included a mixture of

inorganic and organic precursors including elevated concentrations of bromide and other organic DBP precursors. The authors concluded that disinfected produced water brines are potential sources of DBPs and DBP precursors to receiving surface waters. Olmstead also assessed the impact of discharged produced wastewater on surface water quality in Pennsylvania (Olmstead et al. 2013). This study developed a geographic information system (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 WWTP releasing treated waste to surface water and increased downstream chloride (Cl^-) concentrations, and between the upstream density of well pads and increased downstream total suspended solid (TSS) concentrations were identified. Conversely, no significant relationship between wells and downstream Cl^- concentrations or waste treatment and downstream TSS concentrations were reported. Results suggest that that upstream shale gas wells do not increase Cl^- concentrations but the treatment and release of UNGD wastewater do. The authors also suggest that increases in downstream TSS associated with UNGD may be due to land clearance for infrastructure development. Drilling companies in Pennsylvania were advised to stop disposing of wastewater through WWTP in 2011 by the Department of Environmental Protection (DEP) (Ferrar et al. 2013a) and the composition of WWTP effluent prior to, and after, this voluntary intervention was assessed. Samples were taken from three WWTP (two public and one private) and analysed for 14 analytes. Results showed levels of several analytes, including Ba, Sr and bromides, exceeded the MCL in samples taken prior to the DEP advice. It is important to note that the MCL relates to the finished drinking water and levels could change before that stage. Samples taken after the DEP advice showed that the levels of most analytes decreased significantly ($p < 0.05$) although the study could not specifically identify UNGD as the source.

Warner also examined the impact on surface water quality following discharge of treated Marcellus liquid wastes (including UNGD derived) during 2010–2012 (Warner et al. 2013b). 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. Concentrations of these major elements in the treated wastewater reflected the composition of Marcellus produced waters. Levels varied during the sampling period with some concentrations up to 6700 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 conclude that while treatment reduces the levels of contaminants, wastewater effluent discharge to surface water has a ‘discernable impact’. Wastewater samples from three impoundments in southwestern Pennsylvania were sampled in 2010 and 2013 to examine the fate of, and potential health effects of exposure to, the most common NORM component radium-226. Each impoundment contained around five million gallons; two contained untreated wastewater and one held wastewater that had been treated by aeration and sulphate addition (Zhang et al. 2015). 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. A small pilot study assessed the levels of natural uranium, lead-210 and polonium-210 in private drinking wells within 2000 m of a large hydraulic fracturing operation before and approximately 1 year after the start of drilling (Nelson et al. 2015). Groundwater samples from three residences in Colorado and single samples from surface water and a municipal water supply were analysed. There were no exceedences of standards and no significant changes in levels before and after drilling. Although the results are reassuring, the authors recognise the limitations of such a small sample size and recommend further and more extensive monitoring before and after hydraulic fracturing operations.

Osborn also used chemical characteristics to differentiate the source of methane contamination in active natural gas extraction areas in NE Pennsylvania (Osborn et al. 2011). Comparing levels of methane and higher chain hydrocarbons in private water wells

($n = 60$) serving areas with no wells to areas with more than one well within 1 km found 85% of the total number of wells contained methane but levels were significantly higher in areas proximal to gas wells. The average concentration was 17 times higher in shallow water wells in the proximal zones ($p < 0.05$) exceeding the US-defined action level for mitigation. The maximum recorded level was more than six times the lower range of the action level and more than twice the upper range and was considered an explosion hazard. Chemical characteristics and gas ratios strongly suggest the source to be UNGD activities, and the authors call for improved management, regulation and monitoring. This study has been criticised methodologically and for failing to adequately acknowledge the distances between hydraulically induced fractures and groundwater supplies, the natural migration of methane over millennia and the lack of pre-drilling samples (Schon 2011; Davies 2011). Data from this study were combined with 109 new samples from 49 wells and 83 samples from deeper formations in the region to determine whether there are pathways between deep underlying formations and shallow drinking water aquifers, a potential contamination route that has been widely dismissed given the reportedly large vertical separations and narrow seismic activity zones (Warner et al. 2012). The results indicate groundwater salinisation in some locations due to mixing of shallow groundwater and deep formation brine. Chemical characterisation suggested the potential migration of Marcellus brine through naturally occurring pathways. Another study using a chemical signature to improve source apportionment and building on, and responding to the criticisms of, the Osborn paper reported the contamination of drinking water sources by natural gas wells. Jackson et al. (2013a) analysed 141 drinking water samples from wells across the Appalachian Plateaus province of NE Pennsylvania for natural gases, isotopic signatures and proximity to gas wells. Methane was detected in 82% of samples with an average concentration six times higher in homes <1 km from natural gas wells compared to those further away ($p = 0.0006$). Ethane was identified in 30% of samples with an average 23 times higher in homes <1 km from gas wells ($p = 0.0013$). Propane was detected in 7.5% of samples, all of which were within approximately 1 km ($p = 0.01$). Proximity to gas wells was significantly associated with both

methane and ethane levels ($p = 0.007$ and 0.005 , respectively). The source of this contamination was examined using isotopic signatures and gas ratio characteristics which found that all the methane levels exceeding the US remediation threshold were associated with the industry and that most of the methane signals associated with shale were identified in those samples <1 km from wells. There was also an association with ethane although there were fewer data available and samples from one population close to wells were characteristic of a microbial rather than shale gas extraction source.

In contrast to the reported associations with UNGD, in an industry supported study, Molofsky et al. (2013) assessed the isotopic and molecular characteristics of hydrocarbons in wells in NE Pennsylvania and concluded that the methane concentrations in well waters were not necessarily due to migration of Marcellus Shale gas through fractures. 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 Gas Field finding little relationship. Over 95% of the methane was of microbial origin and neither density of, nor proximity to, oil/gas wells had a significant impact on methane concentration, suggesting other important factors influencing methane generation and distribution. 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. In response to the Osborn and Jackson results a data set of 11,300 pre-drilling samples of domestic well water supplies in the vicinity of 661 oil and gas wells (92% unconventionally drilled) taken between 2009 and 2011 was analysed (Siegel et al. 2015). The density of UNGD in this region of Pennsylvania enabled these ‘pre-drilling’ samples to be matched to one or more existing oil or gas wells reflecting, in the authors’ view, a post-drilling comparison. The multiple analyses conducted found no statistically significant associations between methane levels in well water and proximity to pre-existing oil or gas wells.

The physics of osmotic and capillary forces has been reported as preventing the escape of residual treatment water (that portion of injected fluids not recovered), following a series of experiments conducted on cuttings from a horizontal well in the

Marcellus Shale joint funded by the US Government and Shell (Engelder et al. 2014). A review of the literature on the physical constraints on upward migration of hydraulic fracturing fluid and brine concluded there were several features of sedimentary basins that limit the possibility of rapid upward migration (Flewelling and Sharma 2014). These include inherently low impermeability, the narrow bands of affected rock and the short-term and localised increases in pressure. The review concluded that, even in the case of an upward gradient, flow rates are low and travel times in the order of millions of years. In an earlier paper Flewelling et al. had noted a number of constraints on hydraulic fracture growth and fault movement that mitigated against upward migration of fluid and brine including the energy lost from the fracturing stimulation during the formation of complex fracture networks (Flewelling et al. 2013). They developed a simple physical relationship to describe the upper limit on fracture height growth as a function of hydraulic fracturing fluid volume and compared this to over 12,000 fracturing events which had been mapped with microseismic sensors. They reported that all microseismic events were less than 600 m above well perforations with the great majority being much lower. In addition, areas of shear displacement (including faults) were estimated to be relatively small with radii in the region of 10 m or less. The authors concluded that contamination of shallow groundwater through induced fractures and faults due to hydraulic fracturing of shale formations was not physically plausible.

Concerns about oestrogen and androgen receptor activity of chemicals used in the UNGD process contaminating drinking water supplies prompted a study of ground and surface water from an intense natural gas drilling area in Garfield County, Colorado (Kassotis et al. 2014). This study reported that most water samples from sites with confirmed drilling-related incidents exhibited more oestrogenic, antioestrogenic and/or antiandrogenic activity than reference samples and that 12 chemicals used in the process exhibited similar activities. Twenty-nine water samples from five sites with a reported spill or incident in the previous 6 years together with five surface water samples from the Colorado River, the drainage basin for the region, 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; 89, 41, 12 and 46% of the 39 water samples showed oestrogenic, antioestrogenic, androgenic and antiandrogenic activities, respectively. 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 activities such as agriculture, animal care and wastewater contamination but considered these to be extremely unlikely given the nature of the areas being sampled. Twelve chemicals used in the UNGD process known or suspected to be endocrine disruptors were also tested for oestrogenic activity and demonstrated novel antioestrogenic and antiandrogenic, and limited oestrogenic activities. The authors concluded that the results supported an association between gas drilling and endocrine disrupting chemical (EDC) activity in surface and groundwaters, and although the study did not definitively link such activity to UNGD wells, the authors considered the association to be plausible.

It is worth noting that while the sources of contamination of water resources by UNGD activity are relatively well understood, there is little, if any, understanding of the interactions between the chemicals in the fracturing fluid and naturally occurring chemicals in the well or their potentially adverse consequences (Moore et al. 2014). This contrasts markedly with UNGD's contribution to air pollution.

Health

Despite the potential for exposures to hazardous emissions and releases from UNGD described in the previous sections, the literature on linking those exposures to human health effects is extremely limited. Three occupational health studies suggest a clear potential for effects on health (Rosenman 2014; Esswein et al. 2013, 2014). The exceedences of occupational health criteria for silica at 11 sites in five US states (Esswein et al. 2013) were considered to put workers at risk of silicosis, plausibly accelerated silicosis after only 5–10 years of exposure, and other silica-related conditions including lung cancer, end-stage renal disease, chronic obstructive pulmonary disease, tuberculosis and connective tissue

disease (Rosenman 2014). Rosenman also linked UNGD-driven demand for silica to a marked increase in sand mining which had also increased the risk of silica-related diseases in mine workers. Esswein et al. (2014) also assessed occupational exposure using PBZ data collected from volunteer workers which revealed airborne benzene levels above occupational standards for some work roles (Esswein et al. 2014). In addition, urine samples showed levels of a benzene metabolite that were moderately correlated with full-shift PBZ benzene TWA concentrations ($r = 0.56$) although none exceeded the ACGIH Biological Exposure Index. However, the analysis did not control for key confounding exposures including smoking. Two occupational studies reported no impact on health although neither used personal exposure data (Bloomdahl et al. 2014; Zhang et al. 2015). The former estimated the volatilisation rates of 12 VOCs from flowback pits using concentration data from 35,000 samples to predict local air concentrations. These were used to develop an inhalation exposure assessment for a worker near an open pit for 8 h/day 5 days/week, for 9 months and to calculate hazard quotients, hazard indices and excess cancer risk. None of the hazard quotients exceeded 1 and the mean hazard index was 0.09 although the 97.5 percentile did reach unity, suggesting some potential for adverse effects. The estimates of excess cancer risk were also reassuring being within the upper limit of the acceptable risk range for individual VOCs. In addition, the cancer risk for the five chemicals with cancer risk values were so low the values were summed and remained within the acceptable excess cancer risk range. This study assumed constant weather conditions and used a modelling method for a limited range of VOCs with no exposure data. While the results of the study were reassuring the authors recognised that its limitations precluded a definitive risk assessment. Zhang et al. 2015 used data on Ra-226 levels in impounded wastewater to derive a radiation dose equivalent to estimate direct exposure and the internal dose from inhalation of airborne radionuclides and ingestion of contaminated material. Both the total dose equivalent for on-site workers and the estimated worst-case event were well within the US Nuclear Regulatory Commission limit for the general public. The upper range of the total carcinogenic risk for on-site workers exceeded the EPA trigger for clean-up of

remediation sites although the authors considered the risks to workers as minimal.

Five studies used clinically confirmed health outcomes. The relationship between total inpatient prevalence rates and 25 medical subcategories with well numbers (per zip code) and density (wells per km²) was examined in three Pennsylvania counties during 2007–2011 (Jemielita et al. 2015). There had been a large increase in UNGD development in two of the counties during this period, while there had been no wells in the third county. The total population was 157,311, and almost 93,000 inpatient records were identified. Cardiology inpatient prevalence rates were significantly associated with well numbers ($p < 0.00096$) and density ($p < 0.00096$), and neurology inpatient prevalence rates were also significantly associated with density ($p < 0.00096$). While this study involved a large resident population, there are limitations which are mostly 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 that affects all studies with no direct measure of exposure.

Casey et al. examined the relationship between four adverse reproductive outcomes and proximity to UNGD and level of drilling activity in a retrospective cohort study using data on over 9000 mothers linked to almost 11,000 neonates over 4 years to January 2013 (Casey et al. 2016). Multilevel linear and logistic regression models explored associations between UNGD activity index quartile and term birth weight, preterm birth, the physical health of newborn babies (5-min Apgar score) and small for gestational age (SGA). An increasingly strong association between quartile of UNGD activity and preterm birth was identified. No association was found with the other two outcomes. A post hoc analysis also identified an association between 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; e.g. mother's address was available for 2013 only and this was assumed to be her address during the pregnancy.

A similar method had been used to examine the association of proximity to UNGD and birthweight, SGA and prematurity in SW Pennsylvania for the period 2007–2010 (Stacy et al. 2015). This study, which included over 15,000 live births, found lower birth weight in the 'most exposed' compared with the 'least exposed' populations (3323 ± 558 cf 3344 ± 544 g) and a significantly higher incidence of SGA (OR 1.34; 95% CI 1.10–1.63). There was no significant association with prematurity. The authors recognise the need for larger studies and improved exposure metrics.

In another analysis of adverse reproductive outcomes the relationship between maternal residential proximity to wells and the risk of oral cleft, neural tube defects (NTD), coronary heart defects (CHD), prematurity and low birth weight in almost 125,000 births in Colorado between 1996 and 2009 was examined (McKenzie et al. 2014). Exposure was imputed by calculating tertiles of inverse distance-weighted natural gas well counts within a 10-mile radius of maternal residence (range 1–1400 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.

An industry body funded study examined childhood cancer incidence in Pennsylvania counties before and after establishment of UNGD sites (Fryzek et al. 2013). Standardised incidence ratios (SIRs) and 95% CIs for childhood cancer, childhood leukaemia and central nervous system (CNS) tumours for a pre-UNGD period (1990 to year prior to UNGD, $n = 1874$) and post-UNGD (from year of first UNGD to 2009, $n = 1996$) were calculated. While the SIR for all cancers post-UNGD (1.02; 95% CI 0.98, 1.07) was higher than pre-UNGD (0.94; CI, 0.90 to 0.99), this difference was not statistically significant. This was also the case for childhood leukaemia (SIR before drilling = 0.97; CI 0.88, 1.06, after drilling 1.01; CI 0.92, 1.11). A significantly elevated SIR was found for CNS tumours after drilling (1.13; CI 1.02, 1.25) compared with pre-drilling (0.89; CI 0.79, 0.99). Analysis of the impact of the number of wells revealed a significantly elevated SIR for total cancers for counties with 500 wells or fewer (1.09; CI 1.03, 1.15) but not for counties with more than 500 wells. The authors recognise that SIRs should not be directly compared but actually do so to make reassuring conclusions which have been challenged on other key methodological issues (Goldstein and Malone 2013).

Six studies used self-reported symptoms. A household survey of residents' self-reported symptoms and views on environmental quality was conducted in Washington County, Pennsylvania, during summer 2012, a period during which there were 624 active wells (95% first drilled between 2008 and 2012) (Rabinowitz et al. 2015). Eligible homes closest to 20 random sampling points in each of 38 contiguous townships were visited to establish access to ground-fed water wells. Households were classified according to distance from the nearest well: <1, 1–2 or >2 km. A total of 208 of the 255 eligible households representing 492 residents were included, and an adult occupant was interviewed using a piloted questionnaire covering self-reported symptoms (overall symptoms; dermal, upper and lower respiratory, GI, neurological and cardiovascular) and qualitative assessment of environment. 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 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) compared with households >2 km from the nearest gas well. Environmental risk awareness was significantly associated with reports of all groups of symptoms. This study controlled for several factors, but the sample size is small in epidemiological terms and has other limitations, recognised by the authors, including the self-reported nature of the symptoms, potential bias, the lack of direct exposure measures and the issue of multiple testing. These factors are reflected in the authors' modest recommendation for further research.

A cross-sectional study of patients presenting to a primary care centre in Pennsylvania used a self-administered questionnaire to explore attribution of health perceptions and 29 symptoms to environmental causes including UNGD over 1 week in 2012 (Saber et al. 2014). Of the 72 participants 42% attributed at least one symptom to an environmental cause with 22% identifying unconventional natural gas development. There were two separate 'health' assessments. Twenty-two percentage 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%).

Another analysis of self-reported symptoms and perceptions described two sets of interviews conducted with a 'convenience sample' of residents living close to the Marcellus Shale development who had contacted the researchers through community outreach or had been referred by activists (Ferrar et al. 2013b). The first session involved the interviewing of 33 subjects with open-ended questions on concerns and symptoms. The second session held 19–22 months later involved 20 of the 33 with the

aim of building on relevant issues identified in the first interview including community and individual health impacts and self-reported psychosocial stressors. The majority of participants lived in Pennsylvania counties with intensive UNGD activity, 17/20 owned their gas rights and 8/20 had outstanding litigation against the company. Symptoms of health impacts and sources of psychological stress were compared longitudinally, and participants attributed 59 different health impacts and 13 stressors to the Marcellus development. Stress was the most frequently reported symptom. Perceived health impacts increased over time ($p = 0.042$), while stressors remained constant ($p = 0.855$). This is a small and acknowledged biased sample. The range of identified symptoms is very broad and includes some questionably plausible conditions such as vitamin D deficiency.

A questionnaire-based community health survey was supplemented with environmental data (VOCs in air and heavy metals in well water) from sites close to participants' homes in 14 Pennsylvania counties (Steinzor et al. 2013). This study involved 108 individuals including people recruited by participants and at public events completing a survey instrument. All interviewees reported symptoms (range 2–111) with over 50% reporting more than 20. A wide variety of symptoms was identified including respiratory, behavioural, neurological, muscular, digestive, skin and vision symptoms. Throat and sinus issues increased with residential proximity to UNGD, and an association between odours and some symptoms was also identified. There is real potential for bias in the distribution of questionnaire, and while some environmental data were collected, this small sample study used distance as a proxy for exposure. Thirty-four 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. Nineteen 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 Protection and used as controls, no comparisons with regulatory or advisory standards were made. Twenty-six 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.

An ecological study using interviews of farmers and families from six US states was supplemented with limited exposure, diagnostic and toxicological data to assess impact on humans and animals (Bamberger and Oswald 2012). The families were referred by environmental groups or activists and related to seven conventional well sites (two wells reported in one case) and 18 HVHF sites (25 wells reported in one case and six in another). In addition to collating information on human, livestock and pet health from interviews, the researchers were able to examine two opportunistic natural experiments where livestock had been exposed and non-exposed on the same farms. Exposures were alleged to have occurred through the contamination of water. Virtually all health data were self-reported and included a wide range of symptoms including for humans; neurological, GI, dermatological, headaches, nosebleeds, fatigue and backache; and for animals, mortality, reproductive, neurological, GI and dermatological symptoms.

Outcomes reported for the two incidents detailed included:

- Incident 1: 21/60 cattle exposed to fracking fluid had died and 16 failed to calve. There were no deaths of the 36 non-exposed cattle and one failure to calve (no significance levels reported).
- Incident 2: 70/140 exposed cattle died with no deaths in the 60 non-exposed.
- A child was reported as suffering fatigue, GI, throat and back pain. Following animal deaths on the farms, toxicological testing of the child showed elevated levels of arsenic but the metal was not found in drinking water. Further tests on the family and the residents of the neighbouring farm showed evidence of benzene exposure, but no analyses had been conducted prior to HVHF starting.

The paper recognises some of its limitations and acknowledges the paucity of available data. All the subjects were referred by environmental groups/activists, and the analysis used self-reported symptoms with no control populations with exception of the 'natural experiments'. Twenty-one of the interviewees were followed up 15–34 months after the initial interview and questioned about subsequent exposures and health effects (Bamberger and Oswald 2015). 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. This follow-up study is compromised by several of the same issues as its predecessor.

Nine studies, including Zhang 2015 and Bloomdahl 2014 discussed above, used derived hazard indices. Chronic and subchronic non-cancer hazard indices were calculated and, for exposure to hydrocarbons, cancer risks for residents living <1/2 mile and >1/2 mile from wells in Garfield Colorado (McKenzie et al. 2012). The study included 187 UNGD sites using air quality data from existing routine ambient air monitoring and data collected in Garfield from January 2008 to November 2010 to assess short-term exposures. These data were used to estimate both subchronic and chronic exposures and health risks. Residents living within 0.5 mile of wells were at greater risk for health effects than those >0.5 mile from wells. Subchronic exposures to air pollutants during well completion activities were the most important component of this risk. The subchronic non-cancer hazard index (HI) <0.5 mile was 5 compared to 0.2 for >0.5 mile principally due to exposure to trimethylbenzenes, xylene and aliphatic hydrocarbons. Chronic HIs were 1 and 0.4 for residents ≤0.5 mile from wells and >0.5 mile from wells, respectively. Cumulative cancer risks were 10 in a million for the proximal zone and 6 in a million for residents living >0.5 mile from wells, with benzene as the major contributor to the risk. The authors associated the largest HI to the relatively short-term but high-emission well completion period. This HI is driven principally by exposure to trimethylbenzenes, aliphatic hydrocarbons and xylene, all of which have neurological and/or respiratory effects and for which UNGD was considered the only plausible source. This is a well-conducted study, and the authors acknowledge its limitations. Distance as a proxy for exposure introduces the possibility of exposure misclassification although this is partially addressed by the use of odour complaints to define areas and the risk calculation included monitoring data. The health outcomes are plausible and consistent with risk assessments in the grey literature. The results contrast with a subsequent reassuring deterministic and probabilistic cancer risk assessment (Bunch et al. 2014). It is interesting to note that the air quality data included in this study

were annual averages derived from a monitoring system for regional atmospheric quality as opposed to McKenzie et al. (2012) who used community-level sampling proximal to UNGD which is potentially more relevant for human health risk assessment.

The TCEQ extensive airborne VOC monitoring data were used to inform a human health risk assessment in the Barnett Shale region (Ethridge et al. 2015). While several short-term samples exceeded odour-based AMCVs and levels above typical background were detected downwind of UNGD, only three exceeded health-based AMCVs. All long-term VOC levels were below long-term health-based AMCVs. Hazard quotients and unit risk factor analyses were used to estimate non-cancer and cancer effects, respectively, and indicated no significant increased risks.

A health risk assessment of airborne VOCs close to UNGD wells in SW Pennsylvania suggested that while local people were exposed to levels of HAPs around four times higher than populations remote from gas operations, concentrations of unconventional natural gas-associated VOCs were well below hazardous levels (Swarthout et al. 2015). 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 et al. (2012). A quantitative risk assessment of the excess lifetime cancer risks for residents and workers associated with the levels of PAHs measured in the vicinity of operational well pads in Carroll County, Ohio, found 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) (Paulik et al. 2015).

A health impact assessment was conducted in response to concerns reported by communities in Battlement Mesa (Witter et al. 2013). This analysis 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 (10×10^{-6}) for those living close to wells compared with the risk for those living farther from wells (6×10^{-6}). 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 and that increased traffic associated with the process 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. 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.

An evaluation of the comparative impact of shale gas and coal, conventional gas, nuclear, wind and solar on a range of environmental and toxicological issues reported that shale gas was much less damaging in terms of human toxicity than coal, nuclear or solar although it was worse than conventional gas (Stamford and Azapagic 2014).

Economic and social

Several industry-sponsored reports published online rather than through the peer-review process have highlighted the economic benefits of UNGD. In response six of these analyses, three of which had an academic affiliation, were assessed (Kinnaman 2011). He identified several shortcomings in the analyses including assumptions that all the lease and royalty payments are spent locally, that the great majority of industry expenditure is local, that the level of well activity is a function solely of the current gas price, erroneous interpretation of data, disregard of the possibility of direct spending crowding out other users of the resource and no assessment as to whether the overall benefits of gas extraction exceed the costs. Kinnaman considered the consistent use of the term ‘conservative estimates’ in the industry-sponsored reportage to be misleading and that the estimates were in fact likely to be ‘overstated’. This theme was developed in a review of the physical and social research on UNGD (Lave and Lutz 2014). They noted that where research is available it is not necessarily of adequate quality; e.g. most of the economic analysis is currently speculative with very little of it in the peer-reviewed literature. This was considered at least partly due to the rapid expansion of UNGD since the mid-2000s which had ‘caught policymakers, environmentalists, and communities by surprise, and left physical and social scientists scrambling to catch up with the biosocial consequences’ and inadequate resources available to regulators for research. This lack of funding and research has had other consequences

creating a knowledge vacuum which has left the industry to become a primary source of knowledge about UNGD. They found the research on social and cultural impacts to be overwhelmingly negative. The authors considered that while the landscape disturbance of UNGD sites is relatively small compared with other land-use activities, fragmentation of ecosystems was extensive. This necessitates further research to better protect important habitats, especially given that UNGD is possibly the most substantive change in energy production since the advent of the fossil fuel economy. 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. The wide variance in opinions about the costs and benefits of UNGD has been reported elsewhere with some considering reality lies somewhere these extremes providing the process was managed well (Jackson et al. 2014).

Concerns of a UNGD-related boom-bust cycle have been described in an assessment of the impact of a large increase in natural gas wells in the Rocky Mountain region from 1998 to 2008 including a review of specific case studies which highlighted the spectre of a subsequent local economy ‘bust’ precipitated by a drop in natural gas prices (Haeefele and Morton 2009).

Two econometric methods, propensity score matching (PSM) and panel-data techniques, were used to both isolate and quantify the effect of UNGD on local income and employment (Paredes et al. 2015). The PSM estimation of the growth rate of per-capita income and employment included all Pennsylvania counties with an active unconventional natural gas well between 2004 and 2011 ($n = 34$) and two control groups (any US county outside Pennsylvania and counties in New York where UNGD has been banned). The panel study used annual data from 2004 to 2011 to estimate the effect of unconventional natural gas wells on total county employment and income. The direct income effects of Marcellus Shale UNGD activities were found to have had a negligible indirect or induced income impact on the general population in counties with HVHF processes. The local employment effects were more substantial, but many of the new jobs were low-paid and accordingly may have been taken by outsiders who tend to spend/send their income home.

Economic benefits of a number of shale booms have been described (Sovacool 2014). These included about 29,000 new jobs and \$238 m 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. However, the review also identified the complexities and expense of the process that can lead to cost overruns, accidents and leakages, and concluded that the benefits of shale gas production are uncertain and conditional on the 'right' mix of technological systems; operating procedures, government regulations and corporate values at each locality. The variation in the literature highlighting the challenge of capturing accurate data on workers' place of residence has been noted together with concerns that increases in state and national employment may have little benefit to those localities faced with the costs of increased UNGD (Wrenn et al. 2015). This analysis of local employment in Pennsylvania combining a data set of local employment with a panel-data difference-in-difference-in-differences model reported that, while Marcellus activity 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, an impact which was halved when considering local employment.

Munasib and Rickman considered that, while unconventional shale gas and oil exploration increased energy sector employment, the impacts on other parts of local economies were poorly understood (Munasib and Rickman 2015). They examined the broader regional economic effects of the industry in three shale plays in Arkansas, North Dakota and Pennsylvania. The analysis included total employment, wage and salary employment, per-capita income, the poverty rate, population, and employment in accommodation and food services, construction and retail sectors. The synthetic control method was used to predict economic activity occurring in the absence of increased unconventional energy development. They reported large and significant positive effects for the oil and gas counties in North Dakota across all regional labour market metrics. However, they also found that significant positive effects in Arkansas were identified only in those counties with the most intensive shale gas

production. This suggests a highly localised positive economic benefit. They considered the positive impacts of the employment effects on the local economy were smaller than those estimated in other analyses and noted the negative impact of rising local goods' prices and adverse effects on the local area 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 offsetting adverse economic effects. Modest increases in employment and income associated with increased UNGD had also previously been reported in an analysis of counties in Colorado, Texas and Wyoming (Weber 2012). This analysis of gas deposit and production data with economic data for 1998/1999 to 2007/2008 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.

Rural North Dakota experienced an oil and UNGD boom in the 2010s estimated to have contributed over a billion dollars to the State's finances, creating 65,000 new jobs and leading to the lowest unemployment level in the USA. 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. The benefits of this 5-year boom, the associated social challenges including impact on local housing, and potential solutions, were assessed through interviews with social workers and Directors of Social Care from across the state (Weber et al. 2014). The latter formed a primary focus group and the former a follow-up group of those working on the periphery of oil activity. The primary group of 20 self-selected participants from the State's 38 directors was interviewed using a semi-structured format. The follow-up group comprised 13 social workers serving the area around the state capital of Bismarck, the largest city on the margins of the energy boom. The authors noted housing as a recurrent theme. In particular, inadequate supply and high housing costs were reported, leading to 'gazumping', poor living conditions, increased homelessness, associated failure to recruit workers and the establishment of temporary accommodation (known in the USA as 'man camps'). Social Services Directors reported an increase in child protection

issues, increasing day care shortage and a diminishing supply of foster homes. Data from the police service suggested ‘troubling increases in domestic violence issues disproportionate to population’. Several benefits were also raised including economic development, partnerships with the industry and decreases in benefit support. However, these were regarded as ‘mixed blessings at best’ with some questioning whether local residents were directly benefiting at all as they endured multiple stresses related to the industry. One example cited recognised a major drop in the fuel assistance programme but an increased use of food banks due to higher rents. The authors prudently advise treating their findings with some caution recognising the limitations of this small cross-sectional study.

A part industry-funded statistical analysis of available reserves and the economics of conventional and unconventionally sourced natural gas found that the costs of producing gas from unconventional reservoirs were comparable to those of conventional gas in some cases (Aguilera et al. 2014). The authors concluded that the estimated available reserves can be accessed safely, cost-effectively and with less environmental damage than other fossil fuels, provided appropriate and effective regulation.

A wide range of environmental protection, public health, energy policy, land-use, economic, regulatory, political and climate change issues was reviewed in response to the proposal to introduce UNGD to NY State (Eaton 2013). A density of 3.5 or more wells per km² in highly productive areas was anticipated based on the experience of other shale gas-producing areas. The review considered that the quantification of all the costs and benefits associated with natural gas drilling in, or close to, New York City’s drinking water sources might never be possible. A net benefit is dependent on both wider public acceptance of the process and effective enforcement. The latter was uncertain given the existing political and regulatory environments. While identifying potential benefits for the transition to a low-carbon economy Eaton cautions that these could be outweighed by highly significant environmental liabilities.

Local communities are understandably concerned about any effects a proposed UNGD may have on property values. The real or perceived impacts of shale gas development were examined using hedonic analysis, a technique that uses the trade-offs homebuyers make between property characteristics and price

(Muehlenbachs et al. 2015). The researchers had access to a substantial property sales data set covering Pennsylvania and used both a triple-difference and a difference-in-differences-nearest-neighbour-matching technique, controlling for potential confounders, to estimate local effects while accounting for county-level macroeconomic impacts. The analyses show 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). The value of homes on a mains supply showed a small increase. However, it is worth noting that the latter was only applicable to homes proximal to *producing* wells, which in the USA would provide homeowner royalty payments, and is dependent on the wells not being visible from the property.

The potential implications for UK property and investment were reviewed in a professional briefing note based on internet resources, albeit using largely respectable peer-reviewed papers and government and other agencies’ research (Jones et al. 2014a). They suggest that the exploratory process in the UK is more expensive than in the USA at £6 million cf £2.4 million. The paper quotes one of the largest US insurance and financial services companies ‘UNGD-related losses have never been a covered loss under personal or commercial policies’, ‘from an underwriting perspective we do not have a comfort level with the unique risks associated with the UNGD process to provide coverage at a reasonable price insurance’ and risks potentially associated with UNGD ‘are not part of our contracts and this is common across the industry’. The review also identifies emerging problems with obtaining mortgages and media sources suggesting some mortgage providers being unwilling to offer mortgages for dwellings within 300 ft of a site with shale gas rights. In England, a leading firm of surveyors considered that while it was too soon to confidently evaluate the impact on property values ‘house prices could fall by as much as 30%’. Jones also highlights concerns that the government guidance provided for planning authorities in the UK is inadequate (Jones et al. 2014b). Witter’s 2013 HIA 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 (Witter et al. 2013).

The effect of proximity to UNGD sites on willingness to purchase property compared four environment,

viz. ‘heavy’ fracking sites (fracking 0.25 mile away, house supplied by well water and drill site visible), ‘light’ fracking sites (fracking one mile away not visible from the property, house served by well water), a business park development and a closed petrol station with leaking underground storage tanks (LUST) (Throupe et al. 2013). Of 194 Texan respondents, 26% were willing to offer a bid in the heavy fracking option. The maximum offer varied from 0.1 to 100% of their valuation (the former representing a 99.9% discounting) with a mean discounting of 34%. The average discount of the top 50% of potential bidders was 20%. A higher proportion of the 177 Gulf Coast Floridian respondents of 36% were prepared to bid but their discounts were larger: mean 50%, with 29% the average for the top 50%. A total of 183 Gulf Coast Floridians were also asked about their intentions for the light fracking option. Thirty-seven percentage confirmed they would make an offer with a discounting range of 0% to almost 100%, a mean of 41% for the whole sample, and 17% for the top half of the market. These discounts are approximately 10% less than for the heavy fracking scenario. Respondents had lower willingness to buy and higher discounts for both UNGD options than the business park option but higher willingness to pay and lower discounting compared to petrol stations with LUST. Interestingly, there were higher levels of discounting related to the UNGD options in areas unfamiliar with petroleum extraction, perhaps reflecting a stigma associated with the process.

While the impact on US property values has been under-researched, increased demand and costs of rental properties could be expected due to the demand created by transient workers (Barth 2013). The environmental risks associated with the process have led to some reports of ‘a large and significant reduction in house prices’ and difficulties in obtaining property insurance and a negative impact on future construction and economic development. In this wide-ranging review Barth also recognised that while the shale gas industry will generate some local and regional jobs and revenues, the levels of both are probably exaggerated in the industry-funded literature. Some studies have used inappropriate economic modelling, e.g. inter-industry coefficients to assess growth in local ancillary and other industries. The experience of a state such as Texas with its long-established extractive industry infrastructure cannot legitimately be applied

to areas new to UNGD which would require the import of key skilled staff (who often send money home rather than spending it locally), materials and services. In addition, such areas are predominantly non-urban with smaller populations and lower economic diversity which will reduce any economic benefit. These areas’ economies are often dependent on agriculture, tourism, organic farming, hunting, fishing, outdoor recreation, and wine and brewing, all of which are highly sensitive to large-scale industrialisation and potential water, air and land contamination. Large-scale UNGD imposes additional costs on local social, health and emergency services as well as the environmental costs such as traffic congestion and road damage. It is estimated, for example, that Marcellus UNGD-related heavy truck traffic caused up to between \$13–23,000 of damage per well to state maintained roads in 2011 (Abramzon et al. 2014). These are stressors that such communities are less able to manage or mitigate and there are concerns 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 (Haeefele and Morton 2009).

The effect on agriculture was also examined following a study reporting a decline in cow numbers and milk production in drilled areas (Adams and Kelsey 2012). Milk production, number of cows and average milk production per cow in five Pennsylvania counties with the most unconventional drilling activity were compared to six neighbouring counties with fewer than 100 wells drilled from 1996 through 2011 with a particular focus on the period 2007 through 2011, a time of large-scale increase in UNGD activity (Finkel et al. 2013). The number of milk cows in the most fracked counties fell substantially (range –18.3 to –46.7%). Of the six comparison counties, there was an 11.5% increase in one, no change in two and a modest decline in three. Declining milk cows numbers were associated, unsurprisingly, with a corresponding decrease in total milk production. The authors recognise the weaknesses in this study and identified other plausible explanations but considered that further research was warranted given the importance of this industry in Pennsylvania.

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 (Popkin et al. 2013). The likely welfare impacts (using WTP as a proxy) of using natural gas extracted by hydraulic fracturing for household electricity were explored in an economic choice experiment (Popkin et al. 2013). The null hypothesis that the difference between mean WTP for New York State electricity produced from hydraulically fractured gas and a 'status quo' option of current electricity supply is zero was tested using data from an Internet survey of 515 households from nine New York counties within the Marcellus Shale region and 18 outside the shale region. New York City was excluded from the study given the scale and magnitude of population, and social and political differences compared to up-state counties. The analysis controlled for key variables including age, gender, educational attainment, place of residence and proximity to UNGD sites. A potential for non-response bias, not necessarily substantive, was noted. While there was variability in the impact with some predicted to gain, New York households were found to incur an estimated welfare loss from HVHF as the source of their electricity of 40–46% of average household electric bills in HVHF counties and 16–20% of bills in areas outside HVHF counties. This equates to respondents being willing to accept UNGD-derived electricity providing their monthly bills were reduced by between \$22 and \$48 (mean bill \$124) with the required discounting increasing with increased proximity to UNGD sites. Respondents generally expressed a preference to continue with the status quo (out of state fossil fuel and nuclear energy). This negative local perception of UNGD is also reflected in a 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 (Bernstein et al. 2013). 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.

Climate change

The most important distal effect of UNGD is its potential contribution to climate change. Shale gas is promoted by the industry and its proponents as a clean source of energy and as a bridge towards a less carbon-dependent sector. However, the resource being extracted and distributed, methane, has a global

warming potential 72 times greater than CO₂ over a 20-year period and its release during extraction and distribution has been documented which has important climate change implications.

Shale gas supplies also have powerful modifying impacts on energy markets and economies dependent on the volumes generated, relative cost, substitution for other fuels, advances in technology, and existing and emerging energy and climate change policies. There are concerns, for example, around the displacement of renewables, an associated increase in coal and oil use, and that future development is dependent on, as yet, uncertain technological breakthroughs in carbon-capture and storage technology to address climate change contribution (Sovacool 2014). The inter-relationship between these factors is complex, and the required careful analysis is hampered by the current uncertainty regarding the frequency and volume of these releases (Moore et al. 2014; Weber and Clavin 2012).

Comprehensive sources of UNGD activity data and associated emission factors are extremely limited. The majority of UNGD greenhouse gas (GHG) emission analyses rely on EPA well completion emission factors developed for the U.S. National GHG Inventory. Although a vital source of information, they have largely been derived from aggregated data (Tyner and Johnson 2014). Methane emissions at natural gas production well pads in routine production or in completion flowback were measured using a top-down wind tracer flux measurements method (Omara et al. 2016). This included 17 well pads with a total of 88 wells and 18 conventional sites with an average of one well per well pad. The average site-level methane emission rate for the well pad sites in routine production was 23 times greater than the mean for the conventional sites. The authors considered this difference to be due to the UNG facility size and higher production rate. Conversely, UNGD sites had much lower production-normalised methane rates which were attributed to better process management. The authors considered the Pennsylvania methane emissions inventory underestimated site-level emissions by up to 40 times for five of UNGD sites included in this study, a difference reflected in an estimate of total VOCs emitted from the oil and gas fields of Weld County Colorado, where the majority of wells produce wet gas, which was twice the state emissions inventory (Pétron et al. 2014). O'Sullivan

and Paltsev estimated methane emissions from nearly 4000 hydraulically fractured US wells during 2010 assuming a variety of controls and concluded that the then current estimate widely used in analyses was exaggerated, particularly if flaring and ‘green completions’ were assumed (O’Sullivan and Paltsev 2012). Black carbon emission factors using data from 26 flares in North Dakota have been reported to be much lower than previous estimates (Weyant et al. 2016).

The impact of increasing natural gas operations during 1996–2013 was examined using ambient levels of ethane, a marker for fugitive natural gas emissions (Vinciguerra et al. 2015). The study accessed hourly data from two EPA Photochemical Assessment Monitoring Stations sited for the Marcellus Shale and a control site in Rockdale Georgia, an area with similar urban sources of pollution but no extensive natural gas production. They reported that daytime ethane concentrations had increased significantly for the former from c.7% of total measured non-methane organic carbon to c.15% from 2010 to 2013. This trend was not observed in the control area and was considered to be linked to the rapidly increasing natural gas production in neighbouring states, especially Pennsylvania and West Virginia. Although other sources of this trend cannot be definitively excluded, the authors conclude that the relationship was plausible and, in the absence of control measures, would continue. Allen examined direct measurements of methane emissions (from May 2012 through December 2012) at 150 production sites, 27 well completion flowbacks, nine well unloadings and four workovers in the US Gulf Coast, Midcontinent, Rocky Mountain and Appalachian production regions (Allen et al. 2013). The production sites contained 489 hydraulically fractured wells. Levels of methane were compared with the 2011 EPA National Emission Inventory. Results for well completion flowbacks were considerably lower than the Emission Inventory while levels for pneumatic pumps and controllers and equipment leaks were either comparable or higher. The study, funded by the Environment Defense League and several energy companies, acknowledged the uncertainties inherent in this type of analysis and calculated that, if the emission factors reported were representative, then total annual emissions from these sources were broadly similar to the national emission inventory. However, most assessments of emission inventories report substantial

underestimates of methane releases with one analysis reporting average methane emissions at the wells up to 23 times greater than the upper range reported by Allen (Goetz et al. 2015). Fugitive methane emissions from oil and natural gas (ONG) operations in the Barnett Shale area were quantified using a mobile laboratory (Lan et al. 2015). Air samples were taken <1.2 km downwind from 152 ONG facilities, including 125 well pads, 13 compressor stations, 2 gas processing plants and 12 landfill sites. Samples were taken at the plume centre line although, given the density of the facilities, emission rates could only be calculated for 36% of the well pads. A more precise model was used where adequate information on emission sources was available. Results indicated that some compressor stations and gas processing plants were disproportionately higher emitters of methane. Modelling showed well pad emissions to be linearly correlated with gas production. While recognising the study limitations including quasi-random site selection, model uncertainties and short duration the authors suggest that the EP Greenhouse Gas Reporting Program (based on self-reported emissions by industry) underestimates emissions from compressor stations and processing plants by up to a factor of 10^4 and some were comparable to a large landfill site. Robust data on methane leakage rates are critical for estimating GHG impact (Allen DT 2014). A study funded by a sustainable shale advocacy foundation reviewed the evidence around methane leaks from North American natural gas systems (Brandt et al. 2014). This reported that official inventories consistently underestimate methane emissions and that a large proportion of leakage could be caused by a small number of ‘super-emitters’, a phenomenon that may skew emission estimates (Lavoie et al. 2015; Subramanian et al. 2015). However, they concluded that hydraulic fracturing is unlikely to be a ‘dominant’ source. In addition, while the natural gas sector was an important source of methane leakage, its contribution would not prevent the climate benefits of substitution for coal. Studies which use top-down measurements consistently report significantly higher leakage rates than those based on bottom-up estimates. Methane emissions from two of the fastest growing US unconventional oil and gas production regions during 2006–2008 and 2009–2011 were estimated using satellite observations and a mass-balance approach (Schneising et al. 2014). They estimated leakages

(energy content) of 10.1 ± 7.3 and $9.1 \pm 6.2\%$ agreeing with Brandt that existing inventories underestimated fugitive releases, the level of which they considered seriously undermined claims of a climate benefit associated with shale. Aircraft-based monitoring over the Marcellus Shale region in 2012 reported a large regional methane flux (Caulton et al. 2014). The analyses also showed that the methane emission flux from the drilling phase was two to three orders of magnitude greater than inventory estimates for some well pads. The authors considered the emissions to be so ‘surprisingly high’ as to be a national issue. The uncertainty inherent in top-down and bottom-up estimates was reduced in a study using repeated mass-balance measurements, ethane as a fingerprint for source attribution, a more complete count of facilities and the integration of multiple ground-based measurement data sets (Zavala-Araiza et al. 2015a). This analysis from the Barnett Shale region reported that half of methane emissions were accounted for by just 2% of facilities with 90% of emissions due to 10% of sites. In addition, their estimates of methane emission releases were significantly higher than those based on public inventories. Acknowledging the importance of apportioning methane emissions from shale formations to the hydrocarbon products, Zavala-Araiza also used mass, energy and economic value basis allocation methods to assign emissions to the three main products of production activity: saleable natural gas, oil, and natural gas liquids (Zavala-Araiza et al. 2015b). This analysis, while identifying regional variability, apportioned c 85% of the emissions to natural gas including an allocation to salable (dry) natural gas about two to seven times lower than those commonly reported. A comprehensive review of the implications of shale gas development for climate change acknowledged that most evidence indicated that substituting natural gas for coal in electricity production and for electricity in buildings (dependent on the mix displaced) and gasoline in transport decreases GHG emissions (Newell and Raimi 2014). However, modelling suggests that without significant fuel policy changes, increased natural gas production will slightly increase overall energy use and stimulate fuel switching including from renewables. The implications of this for GHG are uncertain and dependent on upstream methane emissions. Lower natural gas prices, such as those experienced in the USA, encourage the substitution for coal but also the

substitution away from low-carbon energy sources including nuclear and renewables, the latter concern shared by others (Sovacool 2014; Jackson et al. 2014), and also increases energy consumption. The beneficial GHG effect of natural gas is dependent on, firstly, its displacement of more coal and petroleum than low GHG technologies like nuclear, hydro and renewables, and, secondly, the control of methane emissions from gas systems which are not fully understood. While natural gas can help reduce the costs of achieving GHG reduction goals, the modest GHG reductions attributed to shale gas are not sufficient to substantially change the trajectory of global GHG concentrations. This requires stronger incentives to switch to natural gas, renewables, nuclear, and for carbon capture and sequestration for fossil fuels. The authors call for further research internationally into the likely magnitude of substitution of natural gas for coal against zero-carbon electricity. These themes are echoed in other studies.

An energy system optimisation model was employed to explore how trends in natural gas production could affect emissions of GHGs, VOCs and NO_x based on variable inputs including gas extraction, distribution and use, and alternative policies for GHG controls (McLeod et al. 2014). Scenarios developed included: base case (EPA model); cheap gas (in which UNGD continues to grow); expensive gas; and reduced carbon scenarios included a fossil fuel cap; a GHG fee (reflecting social cost); coal retirements; and conventional natural gas-fuelled vehicles. GHG emissions were estimated to decrease by 1.4% from 2010 to 2050 in the costly gas model. However, emissions were modelled as increasing by 2–3% in both the base case and cheap gas scenarios. For the cheap gas model, a 20-year global warming potential (GWP) of methane of 72 produced an estimated 6% increase in overall energy system GHG emissions between 2010 and 2050 while a 100-year GWP of methane of 25 produced an estimated 3% increase by 2050. Neither the coal retirement nor GHG fee models led to a significant reduction in natural gas production due to exports to neighbouring states in the former, and the fee not being high enough to deter use of gas as an electricity fuel source in the latter. Modelled outputs suggested that variations in natural gas cost and abundance had little impact on overall GHG emissions from the US energy system, due to offsetting changes across

sectors; e.g. in the ‘costly gas’ scenario, increased coal replaced natural gas electricity production. The greatest reductions in GHG emissions were found with the fossil cap scenario (reduction of proportion of fossil fuel generated electricity to 20% by 2050). Nevertheless, in each reduced carbon scenario the Rocky Mountain electricity mix shows greater reliance on wind. NO_x emissions declined in all the scenarios considered. Increased VOC emissions from NG production offset part of the anticipated reductions from the transport sector. In the base, cheap gas and costly gas scenarios NO_x and VOC emissions also decreased by varying amounts between 2010 and 2050.

Assuming an abundant natural gas supply, simulations from five integrated assessment models of energy–economy–climate systems were developed (McJeon et al. 2014). This analysis found that global expansion of UNGD could produce large volumes of economically competitive unconventional gas. However, this increase in global supply does not materially reduce the trajectory of GHG emissions or climate forcing. A projected additional natural gas consumption up to 170% by 2050, for example, would produce a modest effect on CO₂ emissions (from –2 to +11%), and most models reported a small increase in climate forcing (from –0.3 to +7%) associated with the increased use of abundant gas. The authors conclude that while the global use of abundant natural gas may substantially change the energy system, it will not necessarily be an effective substitute for policies to address climate change.

The Massachusetts Institute of Technology Emissions Prediction and Policy Analysis model, developed by consortia including industry bodies, has been used to address concerns about the economics of the US shale gas industry and the legitimacy of using large supply assumptions to frame future environmental policy (Jacoby and O’Sullivan 2012). The model used cost data from a variety of sources to explore the implications of shale gas for two GHG control strategies. Shale gas commercial viability generates contradictory effects both stimulating the national economy and providing the flexibility to cost-effectively meet GHG reduction targets while producing higher emissions than an uneconomic shale projection. While the authors emphasise that their results are illustrative, they conclude that the concerns are overstated. However, they recognise that the modelled regulatory policies used would stifle the market for the

development and use of the low-emission technologies required for more ambitious GHG targets and that shale gas could effectively stymie this market altogether. They use an interesting analogy to articulate this concern ‘while taking advantage of this gift in the short run, treating gas as a bridge to a low-carbon future, it is crucial not to allow the greater ease of the near-term task to erode efforts to prepare a landing at the other end of the bridge’.

Several studies have used life cycle analysis (LCA) to compare shale gas with conventional natural gas and coal. This is important as, while the methane content of conventional and unconventional gas is approximately the same (Hultman et al. 2011), the extraction techniques differ.

A LCA conducted on Marcellus Shale natural gas examined GHG emissions, energy and water consumption under both the then current (2011–2012) and previous (2007–2010) operating practices (Dale et al. 2013). Combustion-derived GHG emissions were similar to conventional natural gas, lower than conventional fossil fuels but higher than unconventional oil sources. Shale gas may represent a decrease in some emissions relative to coal, but it remains insufficient to meet scientific mitigation goals for global carbon emissions. This study emphasises the large uncertainties at various points of the shale gas life cycle and the need to collect data on other key potential issues. A meta-analysis of the available literature has been used to develop robust, consistent and contemporary comparisons of life cycle GHG emission estimates for electricity produced from shale gas, conventionally produced natural gas and coal (Heath et al. 2014). The median estimates of GHG emissions from shale gas-generated electricity on a per unit electrical output basis are similar to those for conventional natural gas, with both approximately half that of coal. However, shale gas life cycle GHG emissions could approach the range of best-performing coal-fired generation in some circumstances. Liquids unloading and estimated ultimate recovery (EUR) of wells were identified as having the largest impact on life cycle GHG emissions. The authors call for further monitoring and improved characterisation of EUR and production practices. Shale gas life cycle emissions were estimated to be 6% lower than conventional natural gas, 23% lower than gasoline and 33% lower than coal in a comparative LCA (Burnham et al. 2012). However, the range in values

for shale and conventional gas overlap and the benefit of using natural gas can be significantly reduced by upstream methane leakage. While natural gas *combustion* produces significantly lower GHG emissions compared to coal and oil, LCA identifies statistical uncertainty as to whether *total* emissions are actually lower. Accordingly, the authors call for improved environmental management and reduced GHG emissions. The estimated life cycle impacts of UK shale gas, assuming its use for electricity generation, have been compared with fossil fuel alternatives and three low-carbon options, viz. nuclear, offshore wind and solar photovoltaics (Stamford and Azapagic 2014). This analysis demonstrates that potential variation of different parameters can result in a wide range of life cycle environmental impacts for shale gas. Some of these are favourable relative to conventional gas and other alternatives, others very unfavourable. The estimates for the GWP of electricity from UK shale gas are consistent with the literature from other countries. For GWP, shale gas is broadly comparable to conventional gas sources. A power plant with 52.5% efficiency (lower heating value (LHV) basis) fuelled by conventional gas has a GWP of 401–508 g CO₂-eq./kWh which overlaps the range for shale gas at 412–1102 g CO₂-eq./kWh. The combustion stage was identified as the most important factor, but the impact was estimated to be considerably worse depending on the amount of gas vented and the EUR per well (among other factors) as identified by Heath et al. (2014). The paper also considered the comparative impact of shale gas and coal, conventional gas, nuclear, wind and solar on a range of other issues including toxicity, abiotic effects and ozone depletion and creation. The results of this comparison are quite complex with little consistency. While shale gas was worse than coal for three impacts considered (photochemical oxidants, terrestrial ecotoxicity and ozone layer depletion) it was better than the renewable options for four (freshwater, marine and human toxicity, and abiotic depletion of elements). Shale gas also had the highest ecotoxicity compared with any of the other technologies. The authors conclude that shale gas appears to be a sound option for the UK in terms of energy security, cost and climate change (despite some of the evidence it presents regarding the latter) providing it can be economically extracted but cautions that the large variations in potential impacts described and the

prospect of other effects requires ‘tight regulation’ for it to be regarded a ‘sound environmental option’. Hultman’s estimate of the greenhouse footprint of shale gas used for electricity generation was around 11% higher than conventional gas but and 56% that of coal for standard assumptions (Hultman et al. 2011); similar results were reported in a LCA of Marcellus Shale gas (Jiang et al. 2011). Howarth’s 2011 estimation of a shale gas GHG footprint at least 20% greater than coal (Howarth et al. 2011) is a significant outlier and has been challenged (Jenner and Lamadrid 2013; Laurenzi and Jersey 2013). The former compared the environmental and health impacts of coal, shale and natural gas recommending more shale and less coal. However, while the shale gas life cycle has a smaller GHG footprint than the coal lifecycle it is larger than that of the conventional gas lifecycle. The latter, of ExxonMobil Research and Engineering Company, conducted a LCA of Marcellus Shale gas in power generation using real production data including gas engine emissions and flowback flaring. Marcellus shale gas production and processing was estimated to contribute 1.2% of the total GHG emissions, statistically indistinguishable from conventional gas. The EUR of the well and the power plant efficiency were identified as the most important factors. Both the carbon footprint and freshwater consumption were around half that of coal, and the authors conclude replacing coal with shale gas for power generation could produce substantial GHG reductions and freshwater savings. Estimated ‘well to wire’ (WtW) emissions of shale gas when used for power generation were found to be considerably lower than for coal and broadly comparable (1.8–2.4% higher) with conventional gas (Stephenson et al. 2011). The authors’ conclusions, all employees of Shell, are reassuring but they acknowledge that in extreme conditions shale gas WtW emissions could be up to 15% higher than conventional gas and this estimate presumes effective flaring and recovery measures. A review of Howarth’s 2011 analysis also estimated that the long-term shale gas GHG impact was less than coal over long term once its higher power generation efficiency was taken into account (Wang et al. 2011). They considered that existing technologies could reduce the short-term impact to less than coal. In addition, there is potential for using depleted shale gas reservoirs to store CO₂ cost-effectively reducing GHG impact further. A probabilistic model was used to estimate the GHG

footprint of shale gas together with a case study using data from the Montney and Horn River shale gas basins in Northern British Columbia (Shahriar et al. 2014). Their analysis reported a much smaller footprint than that of Barnett Shale (which was considered representative of US shale gas) due to regulatory flaring requirements. The authors also challenged Howarth's estimates.

However, atmospheric methane emission derived from three natural gas production regions which accounted for over 50% of the US unconventional shale gas and approximately 20% of all natural gas production found natural gas loss rates from the Haynesville, Fayetteville and Marcellus study regions as within the range of emissions estimated by Howarth (Peischl et al. 2015). This study used 1-day methane fluxes calculated for early summer 2013 based on measurements taken from a research aircraft. Other potential methane sources such as livestock and landfills were not considered significant. In addition, Howarth's (2014) review of subsequent research and the fifth IPCC assessment reported that the 2011 estimates of methane emissions from shale and natural gas were 'relatively robust' (Howarth 2014).

However, the fundamental positions of, on the one hand, a climate change benefit of natural gas replacing coal in electricity generation and, on the other, a climate change disbenefit of methane leakage from the UNGD process have both been challenged given carbon cycle and climate system timescales (Schrug 2012). In this analysis, the critical issues are cheap natural gas stimulating additional energy demand while suppressing investment in energy efficiency and low-carbon technologies including renewables.

Seismic

It has been known since the 1960s that earthquakes can be induced by fluid injection. The injection of fracking fluid into a fault zone in the UK Bowland Shale induced small but felt earthquakes in April and May 2011 (Marshall 2011). A numerical model developed to estimate the maximum magnitude of similarly induced events concluded they would be too small to cause damage (Baisch 2013), a similar conclusion to Westaway and Younger (2014).

An analysis of an earthquake in Alberta Canada in the vicinity of the Fox Creek UNGD concluded that, while more data were required to definitively link the

earthquake with UNGD, there was a plausible association with local shale gas exploration (Wang et al. 2016). This was the third 'felt' event during the first 6 months of 2015 and occurred a month after hydraulic fracturing activity. Assessment of publicly available records revealed no other major industrial activities associated with oil recovery or wastewater disposal. A series of 116 earthquakes ranging in Richter local magnitude (ML) from 0.6 to 2.9 proximate to a well in Oklahoma during a UNGD operation have been evaluated (Holland 2013). No other earthquakes were identified prior to, or after, fracking. The first earthquake was recorded 24 h after hydraulic fracturing beginning, a delay consistent with the diffusion of pore pressure in the subsurface over a distance of c 2 km. The likelihood of an association is strengthened by the absence of earthquakes during a 2-day break in the fracking and a resumption following the process restarting.

While injection of wastewater will not be permitted in the UK, it is worth noting reported incidences of linked seismic activity in assessing geological plausibility. A total of 198 possible examples of induced seismicity from 66 published papers and reports were examined for evidence for, and mechanics of, faults being reactivated due to hydraulic fracturing (Davies et al. 2013). The review considered the following potential triggers: mine subsidence, oil and gas field depletion, fluid injection for secondary oil recovery, research-related projects, wastewater disposal, solution mining, enhanced geothermal systems operations, reservoir impoundment, groundwater extraction and hydraulic fracturing for recovery of hydrocarbons from shale. A number of plausible pathways for the latter were identified along with mechanisms for reactivating faults due to hydraulic fracturing including fracturing fluid or displaced pore fluid entering a fault, transmission of a pressure pulse and deformation or 'inflation' of the rock. The authors concluded that while the risk of induced seismicity could not be ruled out the magnitude of such activity was small compared to processes such as reservoir impoundment, conventional oil and gas field depletion, water injection for geothermal energy recovery, and wastewater injections. Dynamic triggering of seismic activity in natural settings has been linked to subsurface fluids (van der Elst et al. 2013). This paper described and suggested that increases in deep wastewater injection may have led to dramatically increased seismic activity in the

Midwestern US. The study considers the prospect of distant earthquakes triggering areas of induced seismicity. An initial search of the Advanced National Seismic System earthquake catalogue provided some evidence. While recognising that most injection wells are not associated with large earthquakes, at least half of the 4.5 moment magnitude scale (M_w) or larger earthquakes in the USA interior over the previous decade had been recorded in regions of potential injection-induced seismicity. Three sites were identified as being particularly sensitive: Prague, Oklahoma; Snyder, Texas; and Trinidad, Colorado. Sensitivity to remote triggering was found to be associated with a long delay between the start of fluid injection and the seismicity onset and in those regions experiencing moderate magnitude earthquakes within 6–20 months. The authors postulate that such triggering could be indicative of fluid injection compromising some critical threshold. This appeared to be dependent on decades of injection, the inherent likelihood of a moderate magnitude earthquake in the region and relatively low levels of seismicity within 10 km prior to the first triggering event. The authors emphasise the importance of improved seismic monitoring in areas of subsurface fluid injection. More than 109 small earthquakes (M_w 0.4–3.9) had been detected over 14 months close to a deep fluid injection well used for disposal of UNGD wastewater from Pennsylvania (Kim 2013). These occurred in an area with no known previous earthquakes. The first earthquake was recorded 13 days after injection started and the pattern of events appeared to be related to pressure build-up. Kim concluded that the earthquakes were induced by the fluid injection at a deep injection well due to increased pore pressure along the pre-existing subsurface faults located close to the wellbore.

Conclusion and recommendations

This review has considered 156 peer-reviewed published papers and general reviews on the public health impact of UNGD. This seems an extraordinarily small evidence base to inform decisions about an industry that has produced probably the most significant change in energy policy since the advent of the fossil fuel economy (Lave and Lutz 2014). This evidence base is very modest in terms of quality as well as size. There are no studies, for example, that rigorously

integrate, analyse and interpret UNGD-related exposure *and* health outcome data. This is a major gap in our understanding. UNGD unequivocally presents an exposure hazard. The process uses and/or produces toxic chemicals at every stage of its development, operation and decommissioning, and there are well-understood mechanisms for, and occurrences of, the release of some of these chemicals. The distribution and combustion of the produced gas also inevitably releases chemicals to the environment. However, while there are some signals in the literature as Coram notes (Coram et al. 2014), there is a hugely important distinction between a hazard, the inherent danger of an adverse consequence, and a risk, the likelihood of that consequence actually occurring. There is a reliance in the literature on the modelling or attribution of exposures which inevitably introduces uncertainties although most of the studies reporting monitoring data related to HVHF operations suggest associated elevated levels of airborne pollutants including VOCs and silica, and waterborne pollutants such as VOCs although data on direct source apportionment are critically limited. In addition, where exposure data have been reported they have rarely included monitoring from the periods before, during and after operation. This lack of a serious portfolio of peer-reviewed data interpretation, analysis and characterisation covering appropriate temporal phases of the process, despite its operation on such a large scale for so many years, renders any confident judgment regarding the safety of UNGD extremely problematic. This applies to both air and water monitoring effectively precluding a credible risk assessment of either the direct impacts on the quality of these environmental media or as to their potential as pollutant pathways to human exposure. It is worth noting, however, that while the threat to water supplies could be much lower in the UK due to the commitments of the UK government and industry, the potential for population exposure to air pollutants may be greater than the USA as UNGD sites may well be in closer proximity to population centres given the relative sizes and population densities.

The majority of papers examining health effects report a link to UNGD, but this literature is, if anything, even weaker. Around half of the studies use derived hazard indices or self-reported symptoms, some subjects are self-referred or referred by activists, most involve very small sample sizes, a number of the

symptoms are of questionable plausibility, and very few use a credible exposure measure. As a result this body of work is compromised by the real potential for exposure misclassification, bias, statistical unreliability and questionable spatial, temporal and biological plausibility. It is worth noting that four of the five studies which use clinically confirmed cases and large sample sizes do report associations between residential proximity to UNGD sites and increased risk of plausibly related adverse health outcomes including three studies strongly suggesting adverse reproductive outcomes. The latter particularly requires further research given the evidence of the developmental and reproductive toxicity of many of the chemicals associated with UNGD (Webb et al. 2014; Kassotis et al. 2014). The fifth study, examining local childhood cancer incidence before and after establishment of UNGD sites, reported elevated, albeit not significantly so, levels of all cancers and leukaemia, and an increase in CNS tumours of borderline significance following UNGD operation. The majority of the health-related research focuses on short-term outcomes and ‘traditional’ environmental media issues (Werner et al. 2015). The latter is an especially important criticism given the lack of research into the potential for serious public health nuisance impacts such as noise, 24-h lighting, dust, odours and traffic disruption. Adgate notes this as well as the potential for intra-community differences in the perception of risk and rewards leading to stress in some residents (Adgate et al. 2014). In a UK context, nuisance refers to a legal concept rather than simply an irritation and the significant body of law concerning nuisance going back to the nineteenth century was a fundamental catalyst for the public health movement and reflects the serious, sometimes deadly, impact of these issues.

The literature on the global warming impact of UNGD overwhelmingly reports that the combustion of shale gas for electricity and heating is a less climate damaging alternative to coal (although it is questionable whether coal is really an appropriate benchmark (Coram et al. 2014; Schrag 2012)) and better than, or broadly similar to, conventional gas. However, it is important to consider the *lifecycle* perspective in this context and here the evidence is concerning. There are clear uncertainties about the extent and volume of inevitable fugitive methane emissions during unconventional gas extraction and distribution which could have a powerful effect on its global warming potential.

Again the lack of critical data militates against an informed judgment and is reflected in the calls for more monitoring and research which are consistent features of the literature. Shale gas has also routinely been described by its advocates as a ‘bridge fuel’ for the transition to less carbon-intensive fuel economy. The evidence for this is questionable given its dependence on the development of large-scale carbon-capture and sequestration technologies (Sovacool 2014; Jacoby and O’Sullivan 2012; Schrag 2012), the economic disincentives to do so that ‘cheap’ shale gas creates and its displacement of renewable energy sources and concerns that the span of this ‘bridge’ may be incompatible with the chronology and regulation of shale gas development (Jackson et al. 2014; Sovacool 2014; Howarth 2014; Levi 2013; Schrag 2012; Brown et al. 2009). The apparent ‘orthodoxy’ of seemingly dichotomous positions that shale gas development is either a climate change positive given its advantages compared to coal for electricity generation or a negative due to its associated fugitive methane emissions has been challenged given that its most important climate impact is potentially more likely to be the effects on energy consumption and the development and use of renewables and carbon-capture technologies (Schrag 2012). This analysis articulates a political case for environmentalists ‘recruiting’ the oil and gas industries in the drive to close coal-fired power stations and move towards a low-carbon economy in the USA. This is both interesting and contentious but is implausible for the UK given the respective chronologies of the current coal plant closures and production potential of shale. There is also some evidence from the USA that shale gas production has perversely led to more coal and oil use. The falling price of the gas has incentivised producers to use the UNGD technique to access the more profitable shale oil leading to the USA becoming the world’s biggest producer of crude oil in 2013 (The Economist 2013). Although coal use in the USA has declined, this has been more than made up by the foreign export market meaning that more coal being burned in Europe and Asia (Parenteau and Barnes 2013).

The broader economic case for shale gas, even in the USA where the scale of production has seen major reductions in both energy costs and reliance on imported fuels, is not without its critics, especially in relation to the effects on local economies. Many of the jobs created either require expertise not found locally

or are low-paid appealing to transient workers with a tradition of sending money home rather than spending it locally. In any case, local communities are faced with the major challenges associated with servicing the needs of these workers and the impact of the industry infrastructure on their environment and existing social networks. It has been noted that the majority of the supportive analyses have been industry-sponsored, not subject to peer-review, and have overestimated the benefits. Indeed, the consistent use of the term ‘conservative estimates’ in the industry-sponsored reportage is considered by some to be misleading and that the estimates are in fact likely to be ‘overstated’ (Kinnaman 2011) or even ‘wildly optimistic’ (Hughes 2013). A number of studies have concluded that UNGD may not actually be as profitable as suggested by advocates (Kinnaman 2011), particularly in some economic circumstances (Beaver 2014; Throupe et al. 2013), or indeed not at all once all the costs are taken into account (Sovacool 2014). One of these factors, largely absent from the industry analyses, is the additional social and economic costs imposed on the local communities in terms of property values, availability of mortgages and insurance, availability of safe and affordable housing, the establishment of temporary accommodation, increases in crime, increasing day care shortage, the costs of highway maintenance, and psychological stress (Weber et al. 2014; Barth 2013; Witter et al. 2013). These communities are currently predominantly rural or semi-rural in nature and will be largely such if UNGD proceeds in the UK. The disproportionate health burden of UNGD borne by these communities has been noted (Coram et al. 2014), and there are real concerns about the compatibility of such an industrial process with traditional local economic enterprises such as agriculture and tourism. The undoubted increased tax revenues for regional or national exchequers are of little consolation to these communities, and indeed, there is evidence from the experience of other extractive industries that this generates resentment and a loss of trust in both the industry and authorities (van der Voort and Vanclay 2015). The redistribution of the environmental injustices historically endured by ‘national sacrifice zones’ such as Appalachia to more affluent areas with no previous experience of such industry is creating ‘profound social, cultural and economic shocks for middle class communities losing control over their

environments’ (Lave and Lutz 2014). It is critical that policy-makers considering UNGD proposals are aware of the lessons of history. The phenomena of the ‘resource curse’ and the boom-bust cycle associated with extractive industries are well documented, and there is emerging evidence from the long-established Barnett Shale that, relative to the rest of Texas, local unemployment has actually increased (Barth 2013). Reducing the likelihood of this requires a measured development of the process to enable the economy and society to adjust (Stevens 2003). It should be a fundamental principle that such resource extraction should only be undertaken when it is clear the local benefits outweigh those of leaving the fuel where it is (Perdue and Pavela 2012).

The economic implications of this industry for the UK are perhaps even less convincing. There is little reason to expect that the UK will be immune from the negative environmental and social impacts described elsewhere, and indeed, they may be more profound given the much smaller size of the nation. It is also accepted that shale gas production in the UK will not reduce the domestic price of energy given the level of reserves, the high cost of extraction and the nature of the European energy market (Stevens 2013). Indeed, there are legitimate concerns that UK shale production may not be economically viable at all (Acquah-Andoh 2015).

The literature on seismic effects is very limited and generally reassuring in a UK context, especially as injection of wastewater, will not be permitted but the experience from Groningen NL, albeit in relation to a conventional gas field, is instructive in terms of the importance of transparency, effective compensation schemes, perceived local benefits of the industry and confidence in regulation (van der Voort and Vanclay 2015). The latter is very important given that the paucity of independent data and research appears to have positioned the industry as the pivotal source of intelligence and expertise. Simplistic paeans to ‘tight’ or ‘gold standard’ regulation will very rapidly lose public, political and professional credibility in an era of extraordinary public service cost-cutting. Indeed, concerned communities will be highly sceptical about the need for such a ‘high’ standard of regulation when they are simultaneously being reassured that UNGD is inherently a safe process. There is only one metric for the quality of regulation, effectiveness, and that requires an adequate and assured level of resourcing,

independence and local oversight. It is reassuring that both the UK regulators and nascent industry appear to have learned from some of the negative aspects of the US experience. Full disclosure of the chemicals used by UK operators will be required and storage of flowback water in open lagoons will not be permitted. The industry has committed to a community engagement charter and that sites will be located with access to mains water and close to the main gas distribution network to reduce the number of truck movements and the level of fugitive gas releases, respectively. All proposals will be subject to an Environmental Impact Assessment and, if approved, the industry body has agreed to environmental monitoring before, during and after operation, and to fund local and regional community projects (United Kingdom Onshore Operators Group 2016). While welcome, these controls and initiatives cannot fully address the real concerns about the environmental, health, economic and social impacts of UNGD given the fundamental hazards the process inevitably generates, the proposed scale of the industry and the lack of data and analysis currently available.

Policymakers, planners and investors are faced with a series of pernicious trade-offs and tough choices (Sovacool 2014), and while research is developing it is some way from being able to meaningfully inform those choices. The significance of this responsibly is heightened by the potential consequences of the industry scaling up after its introduction. There are serious gaps in our understanding of the potential impacts, many legitimate concerns derived from first principles, and some concerning signals in the literature which require addressing with a robust research investment (Shonkoff et al. 2014; Adgate et al. 2014; Finkel and Hays 2013; Mash et al. 2014). As Werner concludes ‘the evidence (or lack thereof) is not sufficient to rule out possible health impacts’ (Werner et al. 2015). This uncertainty is also reflected in the grey literature with some recent reviews expressing confidence in the safety of the process given sound operational practices and regulation (Task Force on Shale Gas 2015; The Royal Society and The Royal Academy of Engineering 2012; Public Health England 2014), some being more equivocal (Lightowers 2015) while others highlight the level of risk (AEA Technology 2012; Maryland Institute for Applied Environmental Health School of Public Health 2014) or

even call for a moratorium (New York State Department of Health; McCoy and Saunders 2015). What we do know is that natural gas has been in shale formations for millions of years and will be around for future generations (Finkel and Hays 2013). There is a fundamental requirement for high-quality epidemiological research incorporating real exposure measures covering the periods before, during and post-shale gas extraction, improved understanding of methane leakage throughout the UNGD process and a rigorous analysis of the social and economic impacts in a context of local democratic accountability and equity. In relation to the latter, it is to be hoped that the UK government takes note of the primacy of the decisions of local municipalities about proposed UNGD as, at the time of writing, it has announced its intention to rule on industry appeals against two local planning decisions at a ministerial level.

An ‘a priori’ programme routinely integrating environmental hazard, exposure and health outcome data across large spatial areas would provide valuable data on plausible associations between a range of potential environmental health insults (not simply UNGD) and health effects, direct public health resources more efficiently, and reassure the public that ‘something is being done’ to proactively protect them. It is more than unfortunate that despite repeated calls for such a tracking system over many years (Finkel et al. 2015; Middleton and Saunders 2015; Penning et al. 2014; Finkel and Hays 2013; Saunders et al. 2012) and the required tools and expertise already readily being available that such a programme has not already been established. It is clearly better as Goldstein said ‘to anticipate the potential for harm, and then act proactively, to prevent it’ (Mitka 2012). There will undoubtedly be other novel technologies in the future that challenge the existing knowledge base and an environmental public health tracking programme would provide policymakers, regulators and public health practitioners with essential data and analysis to inform decisions and actions.

As the available evidence does not enable a definitive public health judgment, a position shared by the US Centers for Disease Control (Centers for Disease Control and Prevention), we have a duty to pursue and assess that evidence while ensuring that, in the meantime, communities are not exposed to unacceptable risks. Several countries and North American

states have banned, or imposed moratoria on, hydraulic fracturing including France, Bulgaria, Germany, Scotland, Wales, New York, Nova Scotia, Newfoundland, Quebec and New Brunswick (Finkel et al. 2015). The Wingspread Declaration on the Precautionary Principle counsels that ‘When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not established scientifically. In this context the proponent of the activity, rather than the public, should bear the burden of proof’ (Science and Environmental Health Network 2016). Considering the uncertainties surrounding the health, environmental, social, global warming potential and economic implications of unconventional gas within this internationally recognised framework, it would seem prudent to incentivise further research across all the domains of UNGD-related impact and delay any proposed developments until the products of this investment have been peer-reviewed and assessed. It is recognised that the decision to allow UNGD in the UK will have a major political dimension which is reflected in the UK government reserving the final planning appeal decision to central government rather than the local planning inspector. If UNGD is permitted in the UK local agencies must be adequately resourced to respond to the environmental, social and economic effects, and the commitments by the UK government and industry described above must be rigorously applied together with the establishment of a comprehensive environmental public health tracking system to monitor any emerging risks and focus interventions most effectively.

Appendix 1: Glossary/acronyms

AMCV	Air monitoring comparison values
ATSDR	Agency for Toxic Substances and Disease Registry
BTEX	Benzene, toluene, ethylbenzene and xylene
CHD	Coronary heart defects
CI	Confidence intervals
CNS	Central nervous system
CO	Carbon monoxide

CS ₂	Carbon disulphide
DBP	Disinfection by-products
DEP	Department of Environmental Protection
EDC	Endocrine disrupting chemical
EPA	Environmental Protection Agency
EUR	Estimated ultimate recovery
FPH	Faculty of Public Health
GHG	Greenhouse gas
GI	Gastrointestinal
GIS	Geographic information system
GWP	Global warming potential
H ₂ S	Hydrogen sulphide
HAPs	Hazardous air pollutants
HI	Hazard index
HVHF	High-volume hydraulic fracturing
IRIS	Integrated risk information system
LCA	Life cycle analysis
LHV	Lower heating value
LUST	Leaking underground storage tanks
MCL	Maximum content level
ML	Local magnitude
Mw	Magnitude scale
NIOSH	National Institute for Occupational Safety and Health
NMHCs	Non-methane hydrocarbons
NORM	Naturally occurring radioactive materials
NO _x	Oxides of nitrogen
NTD	Neural tube defects
OEL	Occupational exposure limit
OSHA	Occupational Safety and Health Administration
ONG	Oil and natural gas
PAHs	Polycyclic aromatic hydrocarbons
PEL	Permissible exposure limit
PM	Particulate matter
PSE Healthy Energy	Physicians, Scientists and Engineers for Healthy Energy
PSM	Propensity score matching
REL	Recommended exposure limit sure limit
SGA	Small for gestational age
SIRs	Standardised incidence ratios
SO ₂	Sulphur dioxide
TCEQ	Texas Commission on Environmental Quality

TLV	Threshold limit value
UOG	Unconventional oil and gas extraction
VOCs	Volatile organic compounds
WTP	Willing to pay
WtW	Well to wire
WWTP	Wastewater treatment plant

Appendix 2: Search strategy

1. UNGD: Shale gas, shale gas development, shale gas drill\$, shale gas exploration, shale gas industry, shale gas production, unconventional gas, unconventional gas extraction, frack\$, hydraulic fracturing, fracturing, high volume hydraulic fracturing, HVHF
2. Exposure: Air quality, pollution, water, land, contamination, toxin\$, PAH\$, benzene, methane, metal\$, diesel fume\$, VOC\$, endocrine disrupt\$, PM, particulate matter, particulate\$, naturally occurring radioactive mat\$, fume\$
3. Health: Public health, cancer\$, neurological, neurobehavioral, reproductive, Low birth weight, birth outcome\$, congenital heart defect\$, neural tube defect\$, oral cleft\$, pre term birth\$, stress, occupational health, mental health, mental well-being, conception, infertility
4. Nuisance: Noise, dust, odour\$, odor\$, light, traffic, congestion
5. Climate change: Climate change, green house gas\$, GHGs, methane, energy policy, fuel policy, energy security
6. Economic: Econom\$, local economy, water sustainability, income, employment, disposable income, fuel poverty, rural economy\$
7. Seismicity: Seism\$, earthquake\$, tremor\$

1 and 2, 1 and 3, 1 and 4, 1 and 5, 1 and 6, 1 and 7.

Databases

The following databases were searched:

Ovid Medline, Economic and Social Research Council, Centre for Economic Policy Research.

Citation searches

Reference lists were examined for papers not identified in searches.

Grey literature/internet/key informants

Includes advice from recognised experts in the field and domestic and international government and key institutional websites.

Inclusion/exclusion

Inclusion:

All: English language, no year restrictions, international, national, regional or local effects, exclusively or significantly related to, or specifically considers HVHF and any associated infrastructure, development, operation or legacy activities/impacts.

Exposure: human, all environmental media, measure of exposure (direct or indirect).

Health: clinically diagnosed and self-reported symptoms.

Nuisance/economic: direct or indirect economic, environmental, nuisance and/or social impacts.

Climate change/policy: all GHGs, impact on compliance with fuel/energy and climate change policies and commitments.

Exclusion: animal studies, non-English, anonymous pieces, studies of UNGD technology, environmental exposures based on estimates with no measured data, levels of contamination in waste products with no assessment or estimation of exposure potential, traffic-related accidents (the UK industry will not require the level of heavy vehicle support reported in the USA and elsewhere), non-peer-reviewed commentaries, opinions, editorials, letters to the editor.

Paper review and data extraction

Data extracted to a pre-defined data extraction table. A 10% sample of included papers independently assessed by two reviewers and unresolved anomalies referred to the other authors for resolution.

Appendix 3: Excluded papers

Paper	Reason for rejection
1. Abrahams LS et al. Life Cycle Greenhouse Gas Emissions From U.S. Liquefied Natural Gas Exports: Implications for End Uses. <i>Environ. Sci. Technol.</i> , 2015 , 49 (5), pp 3237–3245	LNG exports
2. Ahmadov R, McKeen S, Trainer M, Banta R, Brewer A, Brown S, et al. 2015. Understanding high wintertime ozone pollution events in an oil- and natural gas-producing region of the western US. <i>Atmos. Chem. Phys.</i> 15:411–429	Oil and gas—no distinction of dominant source
3. Albertson JD et al. A Mobile Sensing Approach for Regional Surveillance of Fugitive Methane Emissions in Oil and Gas Production. <i>Environ. Sci. Technol.</i> , 2016 , 50 (5), pp 2487–249	Describes method for detecting methane
4. Alexander BM et al. The Development and Testing of a Prototype Mini-Baghouse to Control the Release of Respirable Crystalline Silica from Sand Movers. <i>J Occup Environ Hyg.</i> 2016, 13(8):628–38	Testing emission control
5. Allard DJ. Pennsylvania’s technologically enhanced, naturally occurring radioactive material experiences and studies of the oil and gas industry. <i>Health Phys</i> 2015;108(2):178	Presentation
6. Allen DT et al. Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers <i>Environ. Sci. Technol.</i> , 2015 , 49 (1), pp 633–640	Principally natural gas but includes conventional and unconventional and oil. No distinction of dominant source
7. Alvarez, Ramón A, et al. Greater Focus Needed on Methane Leakage from Natural Gas Infrastructure. <i>Proceedings of the National Academy of Sciences</i> 109 (2012): 6435–6440	Examines changes to vehicle fleet as well as use for electricity
8. Asche F et al. <i>Energy Policy</i> , 2012, vol. 47, issue C, pages 117–124	Not an issue for UK
9. Aucott ML and Melillo JM. A Preliminary Energy Return on Investment Analysis of Natural Gas from the Marcellus Shale. <i>Journal of Industrial Ecology</i> , 17: 668–679	Doesn’t address economic (dis)benefits
10. Bern CR, Clark ML, Schmidt TS, Holloway JM, McDougal RR. 2015. Soil disturbance as a driver of increased stream salinity in a semiarid watershed undergoing energy development. <i>J. Hydrol.</i> 524:123–136; doi: 10.1016/j.jhydrol.2015.02.020	Website link. Refers to soil disturbance of any type
11. Binnion, M. 2012. How the technical differences between shale gas and conventional gas projects lead to a new business model being required to be successful. <i>Marine and Petroleum Geology.</i> 31(1): 3–7	Doesn’t address economic (dis)benefits
12. Birdsell DT, Rajaram H, Dempsey D, Viswanathan HS. 2015. Hydraulic fracturing fluid migration in the subsurface: A review and expanded modeling results. <i>Water Resour. Res.</i> 51:7159–7188; doi: 10.1002/2015WR017810	Simulation
13. Bolden AL et al. New Look at BTEX: Are Ambient Levels a Problem? <i>Environ. Sci. Technol.</i> , 2015 , 49 (9), pp 5261–5276	Review of non-cancer health effects of BTEX
14. Boothroyd IM et al. Fugitive emissions of methane from abandoned, decommissioned oil and gas wells. <i>Sci Total Environ.</i> 2016 Mar 15;547:461–9	Abandoned-not relevant to UK
15. Bowen, Z. H., et al. (2015), Assessment of surface water chloride and conductivity trends in areas of unconventional oil and gas development—Why existing national data sets cannot tell us what we would like to know, <i>Water Resour. Res.</i> , 51, 704–71	Oil and gas—no distinction of dominant source
16. Boyle MD, Payne-Sturges DC, Sangaramoorthy T, Wilson S, Nachman KE, Babik K, et al. (2016) Hazard Ranking Methodology for Assessing Health Impacts of Unconventional Natural Gas Development and Production: The Maryland Case Study. <i>PLoS ONE</i> 11(1): e0145368. doi: 10.1371/journal.pone.0145368	Methodological and hypothetical examples
17. Brantley HL, Thoma ED, Eisele AP. 2015. Assessment of volatile organic compound and hazardous air pollutant emissions from oil and natural gas well pads using mobile remote and on-site direct measurements. <i>Journal of the Air & Waste Management Association</i> 65:1072–1082	Oil and gas—no distinction of dominant source

Paper	Reason for rejection
18. Brantley SL, Yoxtheimer D, Arjmand S, Grieve P, Vidic R, Pollak J, et al. 2014. Water resource impacts during unconventional shale gas development: The Pennsylvania experience. <i>International Journal of Coal Geology</i> ; doi: 10.1016/j.coal.2013.12.017	Shortcomings of monitoring of contraventions
19. British Columbia Oil and Gas Commission 2012	Not peer-reviewed
20. Brown D, Weinberger B, Lewis C, Bonaparte H. 2014. Understanding exposure from natural gas drilling puts current air standards to the test. <i>Rev Environ Health</i> 29:277–292; doi: 10.1515/reveh-2014-0002	Inadequacy of air quality standards
21. Brown DR, Lewis C, Weinberger BI. 2015. Human exposure to unconventional natural gas development: A public health demonstration of periodic high exposure to chemical mixtures in ambient air. <i>Journal of Environmental Science and Health, Part A</i> 50: 460–472	Hypothetical
22. Brown SPA et al. Resources for the Future. Natural gas: a bridge to a low-carbon future? <i>Resources</i> 2009;Issue Brief 09-11	Think tank briefing
23. Busch C and Gimon E. 2014. Natural Gas versus Coal: Is Natural Gas Better for the Climate? <i>The Electricity Journal</i> , 27 (7): 97–111	Natural gas in general
24. Burkhart 2013 Potential radon release during fracturing in Colorado. Proceedings of the 2013 International AARST Symposium	Conference proceedings
25. Carlton AG, Little E, Moeller M, Odoyo S, Shepson PB. 2014. The Data Gap: Can a Lack of Monitors Obscure Loss of Clean Air Act Benefits in Fracking Areas? <i>Environ. Sci. Technol.</i> 48:893–894; doi: 10.1021/es405672t	Methodological
26. Cathles LM et al. A commentary on “The greenhouse-gas footprint of natural gas in shale formations” by R.W. Howarth, R. Santoro, and Anthony Ingraffea. <i>Climatic Change</i> , DOI 10.1007/s10584-011-0333-0	Commentary
27. Cathles, L. M. (2012), Assessing the greenhouse impact of natural gas, <i>Geochem. Geophys. Geosyst.</i> , 13, Q06013, doi: 10.1029/2012GC004032	Natural gas in general
28. Caulton DR et al. Methane Destruction Efficiency of Natural Gas Flares Associated with Shale Formation Wells. <i>Environ. Sci. Technol.</i> , 2014, 48 (16), pp 9548–9554	Efficiency of flaring
29. Chabudzinski L, Chmiel S, Michalczyk Z. 2015. Metal content in the waters of the upper Sanna River catchment (SE Poland): condition associated with drilling of a shale gas exploration wellbore. <i>Environ. Earth Sci.</i> 74:6681–6691; doi: 10.1007/s12665-015-4668-0	Exploratory borewell
30. Craddock, H. Shale gas in Europe: The chemical challenge. <i>Materials World</i> . 2014 22 2:41	Magazine article
31. Darbouche H. MENA’s Growing Natural Gas Deficit and the Issue of Domestic Prices”, <i>Energy Strategy Reviews</i> , 2013, 2 (1): 116–121	Not an issue in the UK
32. de Melo-Martin I et al. The role of ethics in shale gas policies. <i>Sci Total Environ</i> 2014 (470–471) 1114	Ethics
33. Edwards PM et al. High winter ozone pollution from carbonyl photolysis in an oil and gas basin. <i>Nature</i> . 2014, 514(7522):351–4	Letter
34. Edwards PM et al. Ozone photochemistry in an oil and natural gas extraction region during winter: simulations of a snow-free season in the Uintah Basin, Utah. <i>Atmos. Chem. Phys.</i> , 13, 8955–8971, doi: 10.5194/acp-13-8955-2013 , 2013	Simulation
35. Elliot TR and Celia MA. Potential Restrictions for CO2 Sequestration Sites Due to Shale and Tight Gas Production. <i>Environ. Sci. Technol.</i> , 2012, 46 (7), pp 4223–4227	Identifies sites suitable for carbon storage and overlap with shale areas that might be developed-hypothetical
36. Entekin SA, Maloney KO, Kapo KE, Walters AW, Evans-White MA, Klemow KM. 2015. Stream Vulnerability to Widespread and Emergent Stressors: A Focus on Unconventional Oil and Gas. <i>PLoS ONE</i> 10:e0137416; doi: 10.1371/journal.pone.0137416	Indices to describe watershed vulnerability

Paper	Reason for rejection
37. Fanchi JR et al. Probabilistic Decline Curve Analysis of Barnett, Fayetteville, Haynesville, and Woodford Gas Shales. <i>Journal of Petroleum Science and Engineering</i> 2013, 50 109:308–311	Production modelling
38. Fedak F et al. Birth Outcomes and Natural Gas Development: Methodological Limitations http://dx.doi.org/10.1289/ehp.1408647 volume 122 number 9 September 2014	Letter
39. Field RA et al. Air quality concerns of unconventional oil and natural gas production. <i>Environmental Science. Processes and Impacts</i> 2014;16(5):954–969	Theoretical
40. Field RA, Soltis J, McCarthy MC, Murphy S, Montague DC. 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. <i>Atmos. Chem. Phys.</i> 15:3527–3542	Oil and gas—no distinction of dominant source
41. Finkel ML and Law A. The rush to drill for natural gas: a public health cautionary tale. 2011 101, 5: 784–785	Commentary
42. Franco B, Bader W, Toon GC, Bray C, Perrin A, Fischer EV, et al. 2015. Retrieval of ethane from ground-based FTIR solar spectra using improved spectroscopy: Recent burden increase above Jungfraujoch. <i>Journal of Quantitative Spectroscopy and Radiative Transfer</i> 160:36–49; doi:10.1016/j.jqsrt.2015.03.017	Not HVHF
43. Freeman CM et al. A numerical study of performance for tight gas and shale gas reservoir systems <i>Journal of Petroleum Science and Engineering</i> 108: 22–39	Doesn't address economic (dis)benefits
44. Gallagher ME et al. Natural Gas Pipeline Replacement Programs Reduce Methane Leaks and Improve Consumer Safety. <i>Environ. Sci. Technol. Lett.</i> , 2015, 2 (10), pp 286–291	Remedial action
45. Gao J and Fengqi U - Shale Gas Supply Chain Design and Operations toward Better Economic and Life Cycle Environmental Performance: MINLP Model and Global Optimization Algorithm. <i>ACS Sustainable Chem. Eng.</i> , 2015, 3 (7), pp 1282–1291	Describes LCA model development-no comparison with other energy sources
46. Gassiat C et al. 2013. Hydraulic fracturing in faulted sedimentary basins: Numerical simulation of potential contamination of shallow aquifers over long time scales. <i>Water Resour. Res.</i> 49:8310–8327; doi:10.1002/2013WR014287	Model to identify conditions needed for slow migration
47. Gentner DR et al. Emissions of organic carbon and methane from petroleum and dairy operations in California's San Joaquin Valley. Emissions of organic carbon and methane from petroleum and dairy operations in California's San Joaquin Valley, <i>Atmos. Chem. Phys.</i> , 14, 4955–4978, doi:10.5194/acp-14-4955-2014, 2014	Not HVHF
48. Gilmore K et al. Transport of Hydraulic Fracturing Water and Wastes in the Susquehanna River Basin, Pennsylvania. 2013, Transport of Hydraulic Fracturing Water and Wastes in the Susquehanna River Basin, Pennsylvania." <i>J. Environ. Eng.</i> , 10.1061/(ASCE)EE.1943-7870.0000810, B4013002	Estimates GHG contribution of transport in a specific area and transport of fracturing water not relevant to UK
49. Goldstein BD The importance of public health agency independence: Marcellus shale gas drilling in Pennsylvania. <i>Am J Public Health.</i> 2014,104(2):e13–5	Lack of public health input to risk assessment
50. Goldstein BD Kriesky J and Pavliakova B <i>Environ Health Perspect.</i> 2012 Apr; 120(4): 483–486	Review of expertise on advisory panels
51. Goodwin S; Carlson K; Knox K; Douglas C; Rein L. Water intensity assessment of shale gas resources in the Wattenberg field in northeastern Colorado. <i>Environmental Science & Technology.</i> 48(10):5991–5, 2014	Efficient water usage-not relevant to UK
52. Graceva F and Zeniewski P. Exploring the uncertainty around potential shale gas development – A global energy system analysis based on TIAM (TIMES Integrated Assessment Model) <i>Energy</i> 2013, 57:443–457	Doesn't address economic (dis)benefits

Paper	Reason for rejection
53. Graham J, Irving J, Tang X, Sellers S, Crisp J, Horwitz D, et al. 2015. Increased traffic accident rates associated with shale gas drilling in Pennsylvania. <i>Accident Analysis & Prevention</i> 74:203–209; doi: 10.1016/j.aap.2014.11.003	Traffic accidents
54. Hammes, U et al. Unconventional reservoir potential of the upper Permian Zechstein Group: a slope to basin sequence stratigraphic and sedimentological evaluation of carbonates and organic-rich mudrocks, Northern Germany. <i>Environ Earth Sci</i> 2013, 70: 3797. doi: 10.1007/s12665-013-2724-1	Resource estimates
55. Harriss R et al. Using Multi-Scale Measurements to Improve Methane Emission Estimates from Oil and Gas Operations in the Barnett Shale Region, Texas. <i>Environ. Sci. Technol.</i> , 2015 , 49 (13), pp 7524–7526	Viewpoint: oil and gas
56. Heilweil VM, Stolp BJ, Kimball BA, Susong DD, Marston TM, Gardner PM. 2013. A Stream-Based Methane Monitoring Approach for Evaluating Groundwater Impacts Associated with Unconventional Gas Development. <i>Groundwater</i> 51:511–524; doi: 10.1111/gwat.12079	Sampling method
57. Helmig - Highly Elevated Atmospheric Levels of Volatile Organic Compounds in the Uintah Basin, Utah <i>Environ. Sci. Technol.</i> , 2014, 48 (9), pp 4707–4715	Gas field but no reference to HVHF
58. Hibbard PJ and Shatzki. The Interdependence of Electricity and Natural Gas: Current Factors and Future Prospects. <i>The Electricity Journal</i> 2012, 25(4):6–17	Not relevant
59. Holahan R and Arnold G. An institutional theory of hydraulic fracturing policy. <i>Ecological Economics</i> 2013, 94 127–134	Doesn't address economic (dis)benefits
60. Howard T et al. Sensor transition failure in the high flow sampler: Implications for methane emission inventories of natural gas infrastructure. <i>J Air Waste Manag Assoc.</i> 2015 65(7):856–62	Implications of sensor failure
61. Howarth, R.W., Santoro, R. & Ingraffea, A. <i>Climatic Change</i> (2012) 113: 537. doi: 10.1007/s10584-012-0401-0	Response to Cathles paper
62. Ikonnikova S et al. Factors influencing shale gas production forecasting: Empirical studies of Barnett, Fayetteville, Haynesville, and Marcellus Shale plays. 2015, Factors influencing shale gas production forecasting: Empirical studies of Barnett, Fayetteville, Haynesville, and Marcellus Shale plays. <i>Economics of Energy & Environmental Policy</i> 2015, 4, (1): 19–35	Doesn't address economic (dis)benefits
63. Jeong S et al. Spatially Explicit Methane Emissions from Petroleum Production and the Natural Gas System in California. <i>Environ. Sci. Technol.</i> , 2014 , 48 (10): 5982–5990	Not HVHF focused
64. Johnson Dr et al. Methane Emissions from Leak and Loss Audits of Natural Gas Compressor Stations and Storage Facilities. <i>Environ. Sci. Technol.</i> , 2015 , 49 (13): 8132–8138	Compares UNG wells with CVNG wells
65. Kahrilas, G. A. Blotevogel, J. Stewart, P. S. Borch, T. Biocides in hydraulic fracturing fluids: A critical review of their usage, mobility, degradation, and toxicity 2015 49 (1) 16–32	Review of considerations in selecting biocides
66. Kaiser MJ. Haynesville shale play economic analysis. <i>Journal of Petroleum Science and Engineering</i> 2012, 82–83:75–89	Economic viability of this play
67. Kaiser MJ. Profitability assessment of Haynesville shale gas well. <i>Energy</i> 2012, 50 38(1):315–330	Doesn't address economic (dis)benefits
68. Kaktins - Drilling the Marcellus shale for natural gas: environmental health issues for nursing <i>The Pennsylvania nurse react-text</i> : 44 66(1):4–8; quiz 8-9/react-text react-text: 47/react-text react-text: 48 March 2011	General overview for nurses
69. Kang M et al. Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. <i>PNAS</i> 2014, 111(51):18173–18177	Abandoned sites

Paper	Reason for rejection
70. Kang M, Baik E, Miller AR, Bandilla KW, Celia MK. 2015. Effective Permeabilities of Abandoned Oil and Gas Wells: Analysis of Data from Pennsylvania. <i>Environ. Sci. Technol.</i> 49:4757–4764; doi: 10.1021/acs.est.5b00132	Abandoned oil and gas wells
71. Karion A et al. Aircraft-Based Estimate of Total Methane Emissions from the Barnett Shale Region. <i>Environ. Sci. Technol.</i> , 2015 , 49 (13): 8124–813	Differentiates between oil/gas-related emissions and other sources but specifically states no attribution to HVHF
72. Karion A et al. 2015 - Methane emissions estimate from airborne measurements over a western United States natural gas field. <i>Geophysical Research Letters</i> 2013, 40(16):4393–4397	Oil and gas—no distinction of dominant source
73. Kerschke DI and Schulz H. The shale gas potential of Tournaisian, Visean, and Namurian black shales in North Germany: baseline parameters in a geological context. <i>Environ Earth Sci</i> 2013, 70: 3817. doi: 10.1007/s12665-013-2745-9	Doesn't address economic (dis)benefits
74. Kopald, D. E. The Conference on Corporate Interference with Science and Health: fracking, food and wireless: genesis, rationale, and results. 2013 28 (4):145–158	Conference proceedings
75. Korfmacher KS et al. Public health and high volume hydraulic fracturing. <i>New Solut.</i> 2013;23(1):13–31. doi: 10.2190/NS.23.1.c	Public health policy discussion
76. Kort EA et al. Four corners: The largest US methane anomaly viewed from space. <i>Geophysical Research Letters</i> 2014, 41(19): 6898–6903	Gas, coal and coalbed methane
77. Koss AR, de Gouw J, Warneke C, Gilman JB, Lerner BM, Graus M, et al. 2015. Photochemical aging of volatile organic compounds associated with oil and natural gas extraction in the Uintah Basin, UT, during a wintertime ozone formation event. <i>Atmos. Chem. Phys.</i> 15:5727–5741; doi: 10.5194/acp-15-5727-2015	Oil and gas—no distinction of dominant source
78. Kovats S et al. The health implications of fracking. <i>The Lancet</i> 2014, 383 (9919): 757–758	Commentary on conference
79. Krzyzanowski - Environmental pathways of potential impacts to human health from oil and gas development in northeast British Columbia, Canada <i>Environmental Reviews</i> , 2012, 20(2): 122–134, 10	Oil and gas—no distinction of dominant source
80. Lamb BK et al. Direct Measurements Show Decreasing Methane Emissions from Natural Gas Local Distribution Systems in the United States. <i>Environ. Sci. Technol.</i> , 2015 , 49 (8): 5161–5169	Distribution systems—all gas doesn't specify UNG
81. Lan X, Talbot R, Laine P, Torres A, Lefer B, Flynn J. 2015. Atmospheric Mercury in the Barnett Shale Area, Texas: Implications for Emissions from Oil and Gas Processing. <i>Environ. Sci. Technol.</i> 49:10692–10700	Oil and gas—no distinction of dominant source
82. Lauver LS Environmental health advocacy: an overview of natural gas drilling in northeast Pennsylvania and implications for pediatric nursing <i>J Pediatr Nurs.</i> 2012 Aug;27(4):383–9	Guidance for nurses on evaluating issue
83. Law A et al. Public Health England's draft report on shale gas extraction. <i>BMJ</i> 2014;348:g2728	Editorial
84. Lee J. The regional economic impact of oil and gas extraction in Texas. <i>Energy Policy</i> , 2015, (56) 87:60–71	University briefing paper
85. Lee, L., Wooldridge, P. J., deGouw, J., Brown, S. S., Bates, T. S., Quinn, P. K., and Cohen, R. C.: Particulate organic nitrates observed in an oil and natural gas production region during wintertime, <i>Atmos. Chem. Phys.</i> , 15, 9313–9325	Oil and gas—no distinction of dominant source
86. Lipscomb, C. A. Wang, Y. Kilpatrick, S. J. Unconventional shale gas development and real estate valuation issues. 2012 42 (2): 161–175	Unavailable

Paper	Reason for rejection
87. Llewellyn GT, Dorman F, Westland JL, Yoxtheimer D, Grieve P, Sowers T, et al. 2015. Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development. PNAS 201420279; doi: 10.1073/pnas.1420279112	Pre-drilling salinisation sources
88. Lu X. Implications of the Recent Reductions in Natural Gas Prices for Emissions of CO ₂ from the US Power Sector. <i>Environ. Sci. Technol.</i> , 2012 , <i>46</i> (5): 3014–3021	US gas prices-not relevant to UK
89. Lyon DR et al. Constructing a Spatially Resolved Methane Emission Inventory for the Barnett Shale Region. <i>Environ. Sci. Technol.</i> , 2015 , <i>49</i> (13): 8147–8157	Oil and gas inventory estimates
90. Mackie P, Johnman C, Sim F. 2013. Hydraulic fracturing: a new public health problem 138 years in the making? <i>Public Health</i> 127:887–888	Editorial
91. Macy TR et al. Carbon Footprint Analysis of Source Water for Hydraulic Fracturing: A Case Study of Mine Water Versus Freshwater. <i>Water Environ</i> 2015, <i>34</i> : 20	Not relevant to UK
92. Marchese AJ et al. Methane Emissions from United States Natural Gas Gathering and Processing. <i>Environ. Sci. Technol.</i> , 2015 , <i>49</i> (17): 10718–10727	All natural gas
93. McCarron GP, King D. 2014. Unconventional natural gas development: economic salvation or looming public health disaster? <i>Australian and New Zealand Journal of Public Health</i> 38:108–109	Commentary
94. McCawley M. Air Contaminants Associated with Potential Respiratory Effects from Unconventional Resource Development Activities. <i>Semin Respir Crit Care Med.</i> 2015, <i>36</i> (3):379–87	No measures and uses traffic volumes as metric
95. McCubbin DR et al. Quantifying the health and environmental benefits of wind power to natural gas. <i>Energy Policy</i> 2013, <i>53</i> : 429–441	Reject-wind power
96. McCubbin –D and Sovacool BK. The Hidden Factors That Make Wind Energy Cheaper than Natural Gas in the United States. <i>Electricity Journal</i> , <i>24</i> (9): 84–95	Wind energy
97. McDermott-Levy R, Kaktins N, Sattler B. Fracking, the environment, and health. <i>2013</i> <i>113</i> (6): 45–51	General implications for nursing
98. McGlade C et al. Unconventional gas – A review of regional and global resource estimates. <i>Energy</i> 2013, <i>55</i> : 571–584.	Resource estimates
99. McKain K et al. Methane emissions from natural gas infrastructure and use in the urban region of Boston, Massachusetts. PNAS 2015 Feb, <i>112</i> (7):1941–6	NG infrastructure and use and not UNG focused
100. Melikoglu M. Shale gas: Analysis of its role in the global energy market. <i>Renewable and Sustainable Energy Reviews</i> 2014, <i>37</i> : 460–468	Doesn't address economic (dis)benefits
101. Meng, Q. Spatial analysis of environment and population at risk of natural gas fracking in the state of Pennsylvania, USA. <i>Sci Total Environ</i> 2015, <i>515</i> –516: 198–206	Uses GIS to map 'risk' defined simply as proximity. No exposure measures or estimates and no health data
102. Miller SM et al. Anthropogenic emissions of methane in the United States. PNAS 2013, <i>110</i> (50): 20018–20022	General assessment of methane sources
103. Mitchell AL and Casman EA. Economic Incentives and Regulatory Framework for Shale Gas Well Site Reclamation in Pennsylvania. <i>Environ. Sci. Technol.</i> , 2011 , <i>45</i> (22): 9506–9514	Doesn't address economic (dis)benefits
104. Mitchell AL et al. Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants: Measurement Results. <i>Environ. Sci. Technol.</i> , 2015 , <i>49</i> (5): 219–3227	All natural gas
105. Moitra, S. Puri, R. Paul, D. Huang, Y.-C T. Global perspectives of emerging occupational and environmental lung diseases. <i>2015</i> <i>21</i> (2): 114–120	General review of potential sentinel occupational diseases

Paper	Reason for rejection
106. Myhrvold NP and Caldeira K. Greenhouse gases, climate change and the transition from coal to low-carbon electricity. <i>Environmental Research Letters Journal</i> 2012, 7(1)	No specific consideration of HVHF
107. Nathan BJ et al. Near-Field Characterization of Methane Emission Variability from a Compressor Station Using a Model Aircraft. <i>Environ. Sci. Technol.</i> , 2015, 49 (13): 7896–7903	Compressor station
108. Oglend - Shale Gas Boom Affecting the Relationship Between LPG and Oil Prices	Not an issue in the UK
109. Ogneva-Himmelberger Y, Huang L. 2015. Spatial distribution of unconventional gas wells and human populations in the Marcellus Shale in the United States: Vulnerability analysis. <i>Applied Geography</i> 60:165–174	Analysis of spatial relationship between socio-economic factors and UNGD sites
110. Olaguer EP et al. Updated methods for assessing the impacts of nearby gas drilling and production on neighborhood air quality and human health. <i>J Air Waste Manag Assoc.</i> 2016, 66(2):173–83	Methodological
111. Olaguer EP. 2012. The potential near-source ozone impacts of upstream oil and gas industry emissions. <i>J Air Waste Manag Assoc</i> 62: 966–977	Hypothetical
112. Oltmans S et al. Anatomy of wintertime ozone associated with oil and natural gas extraction activity in Wyoming and Utah. <i>Elementa: Science of the Anthropocene</i> , 2. 000024	Meteorological
113. Pacsi AP, Alhajeri NS, Zavala-Araiza D, Webster MD, Allen DT. 2013. Regional air quality impacts of increased natural gas production and use in Texas. <i>Environ. Sci. Technol.</i> 47:3521–3527; doi:10.1021/es3044714	Production estimated
114. Pacsi AP, Kimura Y, McGaughey G, McDonald-Buller EC, Allen DT. 2015. Regional ozone impacts of increased natural gas use in the Texas power sector and development in the Eagle Ford shale. <i>Environ. Sci. Technol.</i> ; doi:10.1021/es5055012	Natural gas use
115. Parker KM, Zeng T, Harkness J, Vengosh A, Mitch WA. 2014. Enhanced Formation of Disinfection By-Products in Shale Gas Wastewater-Impacted Drinking Water Supplies. <i>Environ. Sci. Technol.</i> ; doi:10.1021/es5028184	Experimental
116. Patzek TW et al. Gas production in the Barnett Shale obeys a simple scaling theory. <i>PNAS</i> 2013, 110(49): 19731–19736	Doesn't address economic (dis)benefits
117. Peischel J et al. Quantifying sources of methane using light alkanes in the Los Angeles basin, California. <i>Journal of Geophysical Research: Atmospheres</i> 2013;118(10):4974–4990	Not focused on shale
118. Pekney NJ et al. Measurement of atmospheric pollutants associated with oil and natural gas exploration and production activity in Pennsylvania's Allegheny National Forest. <i>J Air Waste Manag Assoc.</i> 2014, 64(9):1062–72	Oil and gas—no distinction of dominant source
119. Penning TM, Breyse PN, Gray K, Howarth M, Yan B. 2014. Environmental health research recommendations from the Inter-Environmental Health Sciences Core Center Working Group on Unconventional Natural Gas Drilling Operations. <i>Environ Health Perspect</i> 122:1155–1159	Working group research recommendations
120. Perry, S. L. Using ethnography to monitor the community health implications of onshore unconventional oil and gas developments: examples from Pennsylvania's Marcellus Shale. 2013 23 (1) 33-53	Methodological
121. Pétron G, Frost G, Miller BR, Hirsch AI, Montzka SA, Karion A, et al. 2012. Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. <i>J. Geophys. Res.</i> 117:D04304	Pilot study-oil, gas and other sources
122. Pétron G, Karion A, Sweeney C, Miller BR, Montzka SA, Frost G, et al. 2014. A new look at methane and non-methane hydrocarbon emissions from oil and natural gas operations in the Colorado Denver-Julesburg Basin. <i>J. Geophys. Res. Atmos</i>	Oil and gas—no distinction of dominant source

Paper	Reason for rejection
123. Phillips NG et al. Mapping urban pipeline leaks: Methane leaks across Boston. <i>Environ Pollut.</i> 2013, 173:1–4	Urban pipeline leaks
124. Powers M, Saberi P, Pepino R, Strupp E, Bugos E, Cannuscio CC. 2015. Popular Epidemiology and “Fracking”: Citizens’ Concerns Regarding the Economic, Environmental, Health and Social Impacts of Unconventional Natural Gas Drilling Operations. <i>J. Community Health</i> 40:534–541	Analysis of letters to local newspaper
125. Pratson LF et al. Fuel Prices, Emission Standards, and Generation Costs for Coal vs Natural Gas Power Plants. <i>Environ Sci Technol.</i> 2013, 47(9):4926–33	Relates to power stations
126. Prenni - Oil and gas impacts on air quality in federal lands in the Bakken region: an overview of the Bakken Air Quality Study and first results. <i>Environ. Sci. Technol.</i> , 2013, 47 (9), 4926–4933	Fossil fuel
127. Rafferty MA, Limonik E. 2013. Is shale gas drilling an energy solution or public health crisis? <i>Public Health Nurs</i> 30:454–462	Call for nursing research and hia
128. Rahm BG, Bates JT, Bertoia LR, Galford AE, Yoxtheimer DA, Riha SJ. Wastewater management and Marcellus Shale gas development: Trends, drivers, and planning implications. <i>J Environ Manage</i> 2013, 120:105–113	Trends in wastewater use and policies
129. Rappenglück B, Ackermann L, Alvarez S, Golovko J, Buhr M, Field RA, et al. 2014. Strong wintertime ozone events in the Upper Green River basin, Wyoming. <i>Atmos. Chem. Phys.</i> 14:4909–4934; doi:10.5194/acp-14-4909-2014	Fossil fuel exploration
130. Reagan MT, Moridis GJ, Keen ND, Johnson JN. 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. <i>Water Resour. Res.</i> 51:2543–2573; doi:10.1002/2014WR016086	Hypothetical
131. Rella CW et al. Measuring Emissions from Oil and Natural Gas Well Pads Using the Mobile Flux Plane Technique. <i>Environ. Sci. Technol.</i> , 2015, 49 (7): 4742–4748	Proportion of emissions by well pad
132. Rich, A Grover, J. Sattler, M. Hunt, A. Holbrook, J. Howard, J. T1 - Air emissions from natural gas exploration and mining in the Barnett shale geologic reservoir. 2012 1 116–133. Proceedings of the Air and Waste Management Association’s Annual Conference and Exhibition, AWMA	Conference proceedings—published in included paper from JAWMA
133. Ritter K et al. Industry experience in deriving updated emission factors to characterize methane emissions for select emission sources in natural gas systems. <i>Carbon Management</i> 2014, 5(5–6): 107	Review of industry efforts to characterise emissions
134. Rodriguez MA, Barna MG, Moore T. 2009. Regional impacts of oil and gas development on ozone formation in the western United States. <i>J Air Waste Manag Assoc</i> 59: 1111–1118	Oil and gas—no distinction of dominant source
135. Rutter AP, Griffin RJ, Cevik BK, Shakya KM, Gong L, Kim S, et al. 2015. Sources of air pollution in a region of oil and gas exploration downwind of a large city. <i>Atmospheric Environment</i> 120:89–99; doi:10.1016/j.atmosenv.2015.08.073	Oil and gas—no distinction of dominant source
136. Sanchez N. and Mays DC. Effect of methane leakage on the greenhouse gas footprint of electricity generation. <i>Climatic Change</i> 2015, 133: 169. doi:10.1007/s10584-015-1471-6	Hypothetical model to identify leakage level required to eliminate advantage over coal
137. Sang W, Stoof CR, Zhang W, Morales VL, Gao B, Kay RW, et al. 2014. Effect of Hydrofracking Fluid on Colloid Transport in the Unsaturated Zone. <i>Environ. Sci. Technol.</i> ; doi:10.1021/es501441e	Colloid transport
138. Schmidt CW. Blind Rush? Shale Gas Boom Proceeds Amid Human Health Questions. <i>Environ Health Perspect</i> 2011, 119:a348–a353	Environews article—subject to internal editing
139. Schnell RC, Oltmans SJ, Neely RR, Endres MS, Molenaar JV, White AB. 2009. Rapid photochemical production of ozone at high concentrations in a rural site during winter. <i>Nature Geosci</i> 2:120–122; doi:10.1038/ngeo415	Letter

Paper	Reason for rejection
140. Schwartz MO. 2014. Modelling the hypothetical methane-leakage in a shale-gas project and the impact on groundwater quality. <i>Environ Earth Sci</i> 73:4619–4632; doi: 10.1007/s12665-014-3787-3	Hypothetical
141. Schwietzke - Natural gas fugitive emissions rates constrained by global atmospheric methane and ethane. <i>Environ. Sci. Technol.</i> , 2014, 48 (14), pp 7714–7722	All natural gas no distinction of dominant source
142. Shearer - The effect of natural gas supply on US renewable energy and CO2 emissions. <i>Environ. Res. Lett.</i> 9 (2014) 094008 (8 pp)	All natural gas no distinction of dominant source
143. Skalak KJ, Engle MA, Rowan EL, Jolly GD, Conko KM, Benthem AJ, et al. 2014. Surface disposal of produced waters in western and southwestern Pennsylvania: Potential for accumulation of alkali-earth elements in sediments. <i>International Journal of Coal Geology</i> 126:162–170; doi: 10.1016/j.coal.2013.12.001	Surface disposal of produced water (not relevant to UK)
144. States S, Cyprych G, Stoner M, Wydra F, Kuchta J, Monnell J, et al. 2013. Brominated THMs in Drinking Water: A Possible Link to Marcellus Shale and Other Wastewaters. <i>Journal - American Water Works Association</i> 105:E432–E448; doi: 10.5942/jawwa.2013.105.0093	Wastes associated with sources including non-HVHF
145. Stephenson E et al. Greenwashing gas: Might a ‘transition fuel’ label legitimize carbon-intensive natural gas development? <i>Energy Policy</i> 2012, 46: 452–459	General discussion of uncertainties
146. Subramanian R et al. Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol. <i>Environmental Science and Technology</i> 2015, 49(5): 3252–3261	Identification of super-emitters and comparison of emissions with EPA emissions
147. Tao Z and Clarens A. Estimating the Carbon Sequestration Capacity of Shale Formations Using Methane Production Rates. <i>Environ. Sci. Technol.</i> , 2013, 47 (19):11318–11325	Relates to carbon-capture capacity
148. Teasdale CJ et al. Ground Gas Monitoring: Implications for Hydraulic Fracturing and CO2 Storage. <i>Environ Sci Technol</i> 2014, 48(23):13610–13616	Technical assessment of ground-level monitoring techniques
149. Thompson CR, Hueber J, Helmig D. 2014. Influence of oil and gas emissions on ambient atmospheric non-methane hydrocarbons in residential areas of Northeastern Colorado. <i>Elementa: Science of the Anthropocene</i> 2:000035	Oil and gas—no distinction of dominant source
150. Townsend-Small A et al. Integrating Source Apportionment Tracers into a Bottom-up Inventory of Methane Emissions in the Barnett Shale Hydraulic Fracturing Region. <i>Environ. Sci. Technol.</i> , 2015, 49 (13): 8175–8182	Methods of source apportionment
151. Tyner DR and Johnson MR. Emission Factors for Hydraulically Fractured Gas Wells Derived Using Well- and Battery-level Reported Data for Alberta, Canada. <i>Environ Sci Technol.</i> 2014, 48(24):14772–81	Relative contribution of differing phases but no analysis of overall significance of UNGD
152. Venkatesh A et al. Uncertainty in life cycle greenhouse gas emissions from United States natural gas end-uses and its effects on policy. <i>Environ. Sci. Technol.</i> , 2011, 45 (19): 8182–8189	Domestic and imported natural gas
153. Wakamatsu H and Aruga K. The impact of the shale gas revolution on the U.S. and Japanese natural gas markets. <i>Energy Policy</i> 2013, 62 (C): 1002–1009	Changes in US and Japanese natural gas market structures
154. Walters K, Jacobson J, Kroening Z, Pierce C. 2015. PM2.5 Airborne Particulates Near Frac Sand Operations. <i>J. Environ. Health</i> 78: 8–12	Not HVHF
155. Walton J and Woocay A. Environmental issues related to enhanced production of natural gas by hydraulic fracturing. 2013 8 (1) 62–71	Non-peer-reviewed section of journal
156. Warneke C et al. PTR-QMS versus PTR-TOF comparison in a region with oil and natural gas extraction industry in the Uintah Basin in 2013. <i>Atmos. Meas. Tech</i> 2015, 8: 411–420	Methodological

Paper	Reason for rejection
157. Warneke C, Gseleger F, Edwards PM, Dube W, Pétron G, Kofler J, et al. Volatile organic compound emissions from the oil and natural gas industry in the Uinta Basin, Utah: point sources compared to ambient air composition. <i>Atmos. Chem. Phys. Discuss</i> 2014, 14:11895–11927; doi: 10.5194/acpd-14-11895-2014	Differentiates between the composition of emissions from oil and gas wells but no discussion of significance in terms of exposure/GHG
158. Warner NR, Darrah TH, Jackson RB, Millot R, Kloppmann W, Vengosh A. 2014. New Tracers Identify Hydraulic Fracturing Fluids and Accidental Releases from Oil and Gas Operations. <i>Environ. Sci. Technol.</i> ; doi: 10.1021/es5032135	Methodological
159. Weber - A decade of natural gas development: The makings of a resource curse? Selected Paper prepared for presentation at the Agricultural & Applied Economics Association's 2013 AAEA & CAES Joint Annual Meeting, Washington, DC, August 4–6, 2013	Paper prepared for presentation at meeting and single author's own views
160. Weijermars R. Economic appraisal of shale gas plays in Continental Europe. <i>Applied Energy</i> 2013,106:100–115	Economics of the process not impacts
161. Weijermars R. US shale gas production outlook based on well roll-out rate scenarios. <i>Applied Energy</i> , 2014, 124 (C): 283–297	Doesn't address economic (dis)benefits
162. Weinhold B. 2012. The Future of Fracking: New Rules Target Air Emissions for Cleaner Natural Gas Production. <i>Environ Health Perspect</i> 120:a272–a279	Discussion of revised regulation
163. Wennberg - On the Sources of Methane to the Los Angeles Atmosphere. <i>Environ. Sci. Technol.</i> , 2012, 46 (17), pp 9282–9289	Fossil fuel emissions—no distinction of HVHF
164. Wigley TML. Coal to gas: the influence of methane leakage. <i>Climatic Change</i> 2011, 108: 601. doi: 10.1007/s10584-011-0217-3	Theoretical, letter
165. Williams JF, Lundy JB, Chung KK, Chan RK, King BT, Renz EM, et al. 2014. Traumatic Injuries Incidental to Hydraulic Well Fracturing: A Case Series. <i>Journal of Burn Care & Research</i> 1; doi: 10.1097/BCR.0000000000000219	Not available-relates to occupational burn injuries
166. Witter RZ Tenney L Clark S Newman LS. Occupational exposures in the oil and gas extraction industry: State of the science and research recommendations. 2014 57 (7):847–856. <i>American Journal of Industrial Medicine</i> Volume 57, Issue 7, pages 847–856	Review of oil and gas industry-hvhf papers already identified
167. Yacovitch TI et al. Mobile Laboratory Observations of Methane Emissions in the Barnett Shale Region. <i>Environ. Sci. Technol.</i> , 2015, 49 (13): 7889–7895	Assesses utility of monitoring method—no assessment of overall GHG impact of UNGD
168. Yao Y et al. Understanding variability to reduce the energy and GHG footprints of U.S. ethylene production. <i>Environ. Sci. Technol.</i> , 2015, 49 (24): 14704–14716	Ethylene
169. Yao Y, Chen T, Shen SS, Niu Y, DesMarais TL, Linn R, et al. 2015. Malignant human cell transformation of Marcellus Shale gas drilling flow back water. <i>Toxicology and Applied Pharmacology</i> 288:121–30; doi: 10.1016/j.taap.2015.07.011	Oil and gas—no distinction of dominant source
170. Yuan B et al. Airborne flux measurements of methane and volatile organic compounds over the Haynesville and Marcellus shale gas production regions. <i>Journal of Geophysical Research: Atmospheres</i> , 2015, 120(12): 6271–6289	Assessment of analytical method
171. Zavala-Araiza D et al. Toward a Functional Definition of Methane Super-Emitters: Application to Natural Gas Production Sites. <i>Environ. Sci. Technol.</i> , 2015, 49 (13): 8167–8174	Definition of super emitter
172. Zhang L, Anderson N, Dilmore R, Soeder DJ, Bromhal G. 2014. Leakage detection of Marcellus Shale natural gas at an Upper Devonian gas monitoring well: a 3-D numerical modeling approach. <i>Environ. Sci. Technol.</i> ; doi: 10.1021/es501997p	Hypothetical: effectiveness of leakage detection
173. Zhang L, Soeder DJ. 2015. Modeling of Methane Migration in Shallow Aquifers from Shale Gas Well Drilling. <i>Ground Water</i> ; doi: 10.1111/gwat.12361	Hypothetical

Paper	Reason for rejection
174. Zimmerle DJ et al. Methane Emissions from the Natural Gas Transmission and Storage System in the United States <i>Environ. Sci. Technol.</i> , 2015, 49 (15), pp 9374–9383	Covers all natural gas—no distinction of dominant source
175. Zou C et al. Geological characteristics and resource potential of shale gas in China. <i>Petroleum Exploration and Development</i> 2010, 37(6):641–653	Not OECD

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