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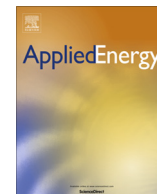
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# Indicative energy technology assessment of UK shale gas extraction <sup>☆</sup>

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## HIGHLIGHTS

- UK shale gas 'fracking' is at a very early stage with an uncertain size of resource.
- Shale gas extraction might benefit UK fuel security, as well as jobs and growth.
- Potentially harmful environmental 'side-effects' must be monitored and regulated.
- Gas bills for UK household and industrial consumers are unlikely to fall sharply.
- Costs & benefits of shale gas fracking are unevenly distributed between communities.

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## ABSTRACT

There is at present much interest in unconventional sources of natural gas, especially in shale gas which is obtained by hydraulic fracturing, or 'fracking'. Boreholes are drilled and then lined with steel tubes so that a mixture of water and sand with small quantities of chemicals – the fracking fluid – can be pumped into them at very high pressure. The sand grains that wedge into the cracks induced in the shale rock by a 'perforating gun' then releases gas which returns up the tubes. In the United Kingdom (UK) exploratory drilling is at an early stage, with licences being issued to drill a limited number of test boreholes around the country. However, such activities are already meeting community resistance and controversy. Like all energy technologies it exhibits unwanted 'side-effects'; these simply differ in their level of severity between the various options. Shale gas may make, for example, a contribution to attaining the UK's statutory 'greenhouse gas' emissions targets, but only if appropriate and robust regulations are enforced. The benefits and disadvantages of shale gas fracking are therefore discussed in order to illustrate a 'balance sheet' approach. It is also argued that it is desirable to bring together experts from a range of disciplines in order to carry out energy technology assessments. That should draw on and interact with national and local stakeholders: 'actors' both large and small. Community engagement in a genuinely participative process – where the government is prepared to change course in response to the evidence and public opinion – will consequently be critically important for the adoption of any new energy option that might meet the needs of a low carbon future.

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## 1. Introduction

### 1.1. Background

Human development is underpinned by energy sources of various kinds that heat, power and transport its citizens in their everyday life. But all energy technologies have unwanted 'side-effects';

they simply differ in their level of severity. Hydraulic fracturing, or 'fracking', for shale gas is a particularly controversial energy option that is receiving significant development support from government in the United Kingdom (UK). Licenses have been issued by the *Department of Energy and Climate Change* (DECC) to drill a limited number of test boreholes around the country (see, for the case of England, [1]). These boreholes are then lined with steel tubes, and a mixture of water and sand with small quantities of chemicals – the fracking fluid – is pumped into them at very high pressure. The sand grains that wedge into the cracks induced in the shale rock by a 'perforating gun' then releases gas which returns up the tubes (see Fig. 1). The UK Government is attracted by the possible benefits of securing large quantities of shale gas for the UK as an energy 'game changer': leading to a potential 'Golden Age of

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Gas', according to the *International Energy Agency* (IEA) [2]. The IEA sees shale gas as contributing about 14% to global gas production by 2035. However, the exploitation of fracking will involve a range of advantages and disadvantages ('credits and debits') that will fall disproportionately on different sections of British society. So it is necessary to identify the components of a shale gas fracking 'balance sheet' of the sort employed in technology assessment [3–5] in order to evaluate its impact on communities, countryside and wildlife, and to determine whether it is compatible with Britain's move towards a low carbon future in 2050 and beyond.

### 1.2. Historical development of fracking for shale gas

The technique of hydraulic fracturing began in the United States of America (USA) [6] in around 1949 when the first two, small-scale commercial vertical wells were initiated in Oklahoma and Texas respectively [7,8]. But it was not until about 1997 that the process known as 'slickwater fracturing' was developed and implemented in the Barnett Shale by the then *Mitchell Energy*. This is a method that involves adding chemicals to water to increase the flowrate at which the fracking fluid can be pumped down a wellbore to fracture extremely dense shale. The fracking fluid is made up of around 98.50% water, 1.00% sand, and 0.05–0.50% chemical additives [6]. These chemicals are friction reducers, usually a polyacrylamide, together with biocides, surfactants and scale inhibitors. Biocides prevent organisms from blocking the 'downhole' and fissures, whereas surfactants keep the sand grains in fluid suspension. Other chemicals that are sometimes employed include benzene, chromium, and a number of other compounds [6]. North American fracking companies keep the composition of this chemical 'cocktail' secret, claiming commercial confidentiality, although an independent study identified about 650 separate chemicals compounds. However in the UK, companies are obliged under the *Water Resources Act* 1991 to disclose the composition used. Many of these are known to be toxic and widespread concern has been expressed over potential water contamination [6,9–11]. Nevertheless, it was this pressure-induced slickwater fracturing (see again Fig. 1) that made shale gas extraction economical by radically reducing the costs of horizontal fracking [6].

The situation with shale gas development in the UK is quite different from that in the USA, where some 200,000 horizontal gas

fracking wells have been in operation over the last two decades or so (Prof. Will Fleckenstein, Colorado School of Mines, USA, private communication 06.11.15) in comparison to just one in Britain – at the Preese Hall site in Lancashire. In addition, the regulatory framework is likely to be tighter in the UK, e.g., 'flowback water' will not be permitted to be reinjected into wells. Environmental limits are also uniformly established across the UK and adherence monitored by national regulators. Water use in the United States (US), by contrast, is regulated on a State-by-State basis.

### 1.3. The issues considered

The possible benefits and disbenefits of shale gas fracking include economic, environmental, safety and social consequences [12] for the UK. Here they are discussed as an example of a 'balance sheet' approach: analysis rather than advocacy. In order to draw up an objective and rigorous set of credits and debits for shale gas fracking (or indeed other potentially 'disruptive' technologies) as part of a national dialogue, it is argued that it is desirable to bring together experts from a wide range of disciplines to undertake *energy technology assessments* (ETA) [5] that exhibit balance, objectivity and broad public participation. This should draw on and interact with national and local stakeholders: 'actors' both large and small. Community engagement will consequently be critically important for the adoption of any new energy option that might meet the needs of a low carbon future. This contribution is part of an ongoing research effort aimed at evaluating and optimising the performance of various sustainable energy systems (see, for example, Hammond et al. [13] and Hammond and Hazeldine [14]) in the context of transition pathways [15,16] towards the statutory target of a reduction in UK 'greenhouse gas' (GHG) emissions by at least 80% by 2050 from 1990 levels [17]. It is aimed at illustrating the consequences of shale gas fracking within a UK setting in the light of imperfect, and sometimes contradictory, information. Nevertheless, such assessments provide a valuable evidence base for communities, developers, policy makers, and other stakeholders. They also yield lessons for other European countries attempting to extract significant quantities of shale gas whilst attempting to decarbonise their energy systems, although local circumstances will obviously limit the wider applicability of the present findings.

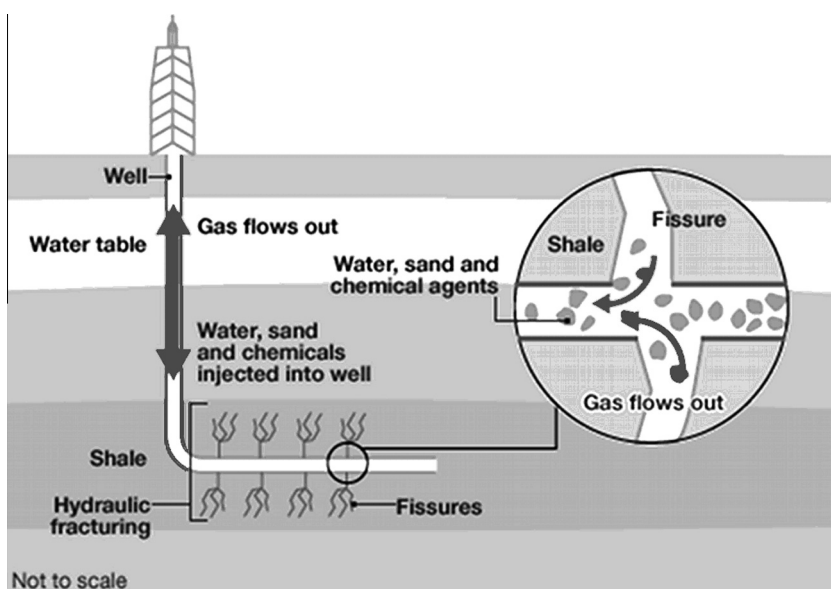


Fig. 1. The shale gas 'fracking' process. Source: adapted from *Transition Haslemere*.

## 2. The potential shale gas resource in the UK

On the positive side of the 'balance equation' is the prospect that fracking could potentially yield significant quantities of shale gas to meet the Britain's energy needs. In contrast (on the negative side), the IEA [2] warn that the significant global development of this gas would put the world on a trajectory towards a long-term temperature rise of over 3.5 °C; well above the widely suggested 'safe' level of 2 °C. The *British Geological Survey* (BGS) [18] has estimated the possible reserves of shale gas in the *Bowland-Hodder* study area or 'play' (encompassing national parks and major cities) and the Weald in the South East for DECC: see Fig. 2. Bassi et al. [19] have also collated several estimates of UK shale gas potential that are presented in Table 1. The great uncertainties inherent in such provisional estimates [total UK technically recoverable shale gas reserves of 150–1130 billion cubic metres (bcm)] can only be refined by extensive investigative drilling, possibly requiring hundreds of wells [20,21]. Notwithstanding the differences between these estimates, they suggest that UK resources are likely to be significant compared to those elsewhere in Europe; given the moratorium on shale gas fracking in France and the limits on extraction in Poland, due to geological constraints [Prof. Danny Reible, Texas Tech University, USA, private communication 05.11.15]. However, making assumptions about recovery rates (based on experience at over 80,000 US horizontal shale gas fracking sites) and the proportion of available resources extractable in the UK, the BGS suggest [18] that recoverable shale gas resources might be equivalent to some 25–50 years of current UK natural gas (NG) demand. That would significantly contribute to Britain's energy security and independence. However, making full use of this resource may not adhere to UK carbon budgets [22] and could risk missing its legally-binding 2050 GHG emissions reduction target.

## 3. Shale gas socio-economic and market issues

The UK balance of payments would obviously benefit significantly from the large-scale development of shale gas extraction, although it is unlikely that gas bills for household and industrial consumers would fall dramatically as they have done in North

**Table 1**

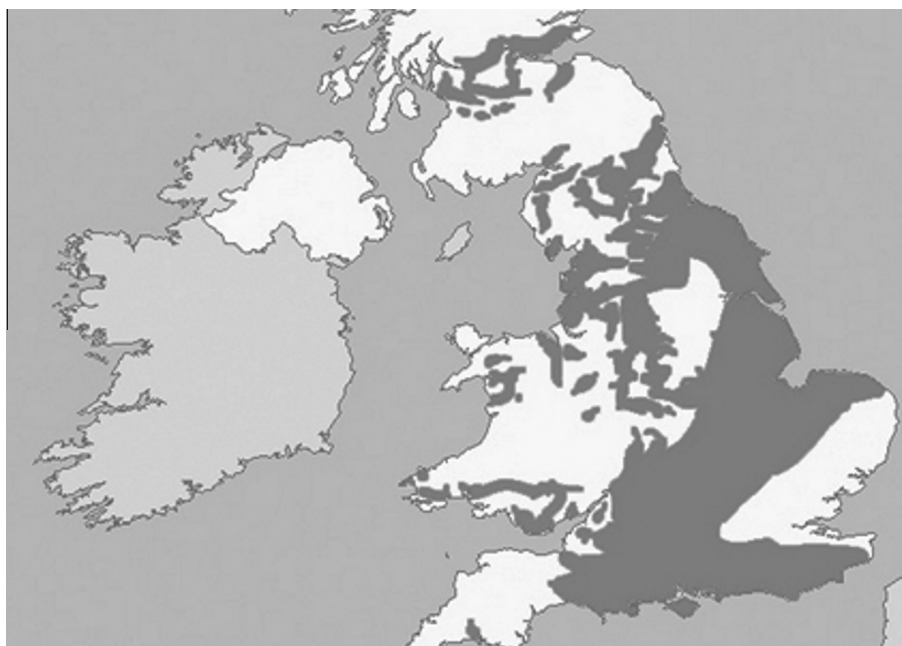
Estimates of shale gas potential in the UK (bcm). Sources: various estimates collated by Bassi et al. [19]; US Energy Information Administration (EIA); Cuadrilla Resources – a UK unconventional gas exploration company; British Geological Survey (BGS); UK Department of Energy and Climate Change (DECC); Energy Contract Company (ECC) – a UK-based commercial oil and gas consultancy.

		EIA	BGS/ DECC	Cuadrilla	ECC
Bowland Shale	Gas in place	2690	–	5660	–
	Technically recoverable	540	80– 200	900– 1200	60– 110
Weald Basin (Liassic shale)	Gas in place	60	–	–	–
	Technically recoverable	30	–	–	–
Total UK	Gas in place	2750	–	–	–
	Technically recoverable	570	150	–	1130

Timescale of estimates: 2011–2012.

Units: billion cubic metres (bcm).

America. This is because the USA is effectively a “natural gas island” with very limited ‘Liquefied Natural Gas’ (LNG) imports via the gas trading hubs of Europe [23]. In the USA, supplies of conventional NG have been drying up, and unconventional gas (including from shales) has been able to grow rapidly to meet some 60% of marketed production, according to the IEA [2]. Many US energy analysts believe that this fall in gas prices to historically low levels has been caused by advances in extraction techniques, particularly fracking, driving down production costs. Much of this shale gas production occurred as an almost ‘free’ co-product of unconventional oil extraction. In contrast, the UK is part of the wider European natural gas market [23] where the gas price is determined by the supply and demand for indigenous natural gas, imports from Russia, and LNG from North Africa and Middle East. Shale gas supplies in the UK will only provide a small fraction of those in this wider gas market. So the household economic benefits in Britain are therefore unlikely to live up to the hopes of the UK Prime Minister (David Cameron), who argued in the *Daily Telegraph* newspaper (11/08/13) that it would “see lower energy prices in this country”. The British *House of Commons* Energy and Climate



**Fig. 2.** Potential UK shale gas reserves [sites – dark shading]. Source: adapted from *Standpoint* magazine, April 2012; after BGS [18].

Change Committee [24] argued that domestic shale gas production could reduce the risk that prices would be determined over the longer term by imports (either via natural gas pipeline or by way of LNG). Nevertheless, they concluded that there is substantial uncertainty over the impact of unconventional gas extraction on market prices. David Cameron also cited job creation as another socio-economic benefit. That will undoubtedly follow successful shale gas exploitation, but it is unclear whether this would be any greater than for equivalent programmes aimed at supporting the adoption of energy demand reduction measures (such as thermal insulation or high efficiency lights and appliances) or small-scale low carbon energy options.

A *Task Force on Shale Gas* (TFSG) was established in the UK in September 2014 funded by several companies with commercial interests in the oil, gas and chemicals sectors [*Centrica, Cuadrilla Resources, Total, The Weir Group, GDF SUEZ E&P UK Ltd.*, and the *Dow Chemical Company* (until September 2015)]. It was led by the former chair of the *Environment Agency* for England and Wales (Lord Chris Smith) with three other 'independent' panel members. However, environmental *non-governmental organizations* (NGOs), such as *Friends of the Earth*, and various local anti-fracking protest groups have expressed skepticism about its claimed impartiality. Nevertheless, it is useful to compare and contrast the findings of the Task Force with those of the present ETA study. Its last report [25] dealt with the potential economic impacts of shale gas extraction in Britain. The TFSG acknowledged at the outset that it is difficult to judge these effects given the uncertainties around the potential availability of shale gas in the UK. In any event, they recognised that such shale gas extraction would have only a minimal impact on the European market for similar reasons to those suggested above. They therefore recommended the drilling of a number of exploratory wells in order to gain a clearer picture of recoverable shale gas in Britain. Despite the uncertainties, they went on to argue that job creation might amount to thousands of jobs directly and many more in the wider supply chain [25], rather in line with the British Prime Minister's assertion noted above. However, the '*Campaign against Climate Change*' Trade Union Group has estimated (backed by eight national unions and aided by six academic specialists) that far more jobs could be generated via equivalent investment in developments that would mitigate GHG emissions [26]. These 'climate jobs' would be created from the adoption of energy conservation measures in the home and in public buildings, renewable energy technologies, clean public transport, and in the development of 'green skills' that will be required through education and training. Based on case studies on the Fylde (the coastal plain in western Lancashire, northern England) and in Salford (a metropolitan borough of Greater Manchester) they suggest that climate jobs could amount to some 14 times those produced directly from the fracking sector and 80 times nationally, i.e., including indirect employment creation across the supply chain. [A breakdown of the one million 'climate jobs' that might be generated by 2030 are shown in Table 2. In addition, Neale [26] argues that half a million additional, or

'spin-off', jobs could also be created.] Such figures are only indicative, although they provide an important contrast to official rhetoric from David Cameron and others about the prospects of employment creation from shale gas fracking.

Perhaps the most important socio-economic issue concerns the distribution of the benefits and costs of shale gas fracking between various communities and demographic groups. Depending on how much shale gas can be exploited, the UK overall could benefit from improved energy security and reduced balance of payments, but it is local communities that will bear most of the risks associated with fracking. The Government intends to offset this potential harm by encouraging (but not requiring) the extraction industry to sign up to a charter that will guarantee payments of some £100,000 to communities located near shale gas exploratory wells. If the gas is ultimately exploited, then they would receive one *per cent* of the resulting revenues: it has been suggested that this might amount to some £10 million. Others have proposed the creation of some form of '*Sovereign Wealth Fund*' (analogous to that generated from Norwegian North Sea oil and gas revenues) to recompense affected UK regions and communities. It is obviously too early to tell how attractive such financial incentives might be to local communities. The *Task Force on Shale Gas* [25] have recommended that operators explain precisely how they intend to provide the £100,000 of local community payments for exploratory well pads and that the beneficiaries should be clearly defined. Properties directly affected by producing wells would obviously face the greatest disruption. The TFSG [25] therefore believe that there should be community involvement in the development of a "fair and robust" community payments scheme.

#### 4. Induced seismicity

Great public concern over shale gas fracking was triggered in 2011 by two seismic tremors, or minor earthquakes (largest reaching  $\sim 2.3 M_L$ ; the local magnitude on the *Richter scale*), caused by exploratory drilling at the *Cuadrilla Resources* site at Preese Hall near Blackpool. Consequently, a moratorium was temporarily placed on shale gas exploration in the UK. Subsequent studies by DECC [27], aided by independent experts, together with a review of the scientific and engineering evidence on shale gas extraction undertaken by the *Royal Society* (RS) and the *Royal Academy of Engineering* (RAEng) [28], found that suitable controls were available to mitigate the risks of undesirable seismic activity. It was argued that the most likely cause of the Preese Hall tremors was 'induced seismicity'; caused by the injection of fracking fluid into and along faults that had already been under stress. The fault then shifts, leading to perceived surface tremors. DECC subsequently announced the introduction of a set of requirements for new controls, permissions and risk assessments on fracking operations in 2012, including oversight by the *Health and Safety Executive* (HSE), at Preese Hall and all future shale gas exploration wells. They included a 'traffic light' seismic monitoring system, as advocated in the RS/RAEng study [28] and subsequently suggested by DECC: *Green* =  $0.0 M_L$ ; *Amber*  $0.0 \leq M_L \leq 0.5$ ; and *Red*  $> 0.5 M_L$  [29]. Nevertheless, earth scientists (see, for example, Davies et al. [30]) viewed the RS/RAEng fault diagnosis as incomplete, and proposed the additional use of borehole imaging before injection. Recently Westaway and Younger [31] suggested that the existing regulatory limits applicable to quarry blasting could be readily applied to cover such induced seismicity. They argued that future fracking activities in the UK is only likely to cause "minor damage", and that seismic monitoring could be used to 'police' compliance with the regulatory framework. The commercially-sponsored UK *Task Force on Shale Gas* (TFSG) in their second report [32] argued that the DECC 'traffic light' limits as possibly being "unfeasibly

**Table 2**

Estimates of potential 'climate job' creation in the UK. Source: Neale [26]. A companion technical report is available online [[http://www.campaigncc.org/sites/data/files/Docs/online\\_companion\\_nov\\_2014.pdf](http://www.campaigncc.org/sites/data/files/Docs/online_companion_nov_2014.pdf)].

Electricity	400,000
Transport	310,000
Buildings	185,000
Industry	25,000
Education	35,000
Agriculture, waste and forestry	45,000
Total UK 'Climate Jobs'	1,000,000

*Timescale of estimates:* job creation over the period to 2030.

low". However, they recommended that independent baseline monitoring should be carried out as early as possible, following the identification of a site to assess seismic risk going forward and also to increase public confidence.

Induced seismic activity has also been linked to the re-injection of large quantities of waste fluid post-fracking, rather than just in the initial hydraulic fracturing process itself [33], which has led to earthquakes of over 5  $M_L$  on the *Richter scale* in the US. A recent study has linked such induced seismicity to disposal wells up to 35 km away [34], much further than previously considered. This practice is unlikely to be carried out in the UK reducing the risk of induced seismicity compared to the USA [29]. It is understood [31] that the reconstituted *Environment Agency* (EA) in England would not grant a permit for this method of wastewater disposal under its current interpretation of the European Union (EU) *Water Framework Directive*. However, the *Task Force on Shale Gas*, again in their second report [32], suggested that there "may be situations and circumstances – where the geology is suitable – where deep injection is sensible, cost effective and popular preferred means of waste disposal". That assertion must be read with an understanding of the commercial interests of the sponsors of the TFSG. In any event, adequate alternative wastewater management systems would need to put in place to safely dispose or reuse of the resultant wastewater [35] away from the fracking site itself.

## 5. Water use and contamination

Fracking for shale gas typically takes place at depths many hundreds of metres (or several kilometres) below drinking water aquifers, although such wells and aquifers do not co-occur everywhere. Unconventional gas enthusiasts argue that there have been no cases of groundwater contamination due to fracking in the United States, but the US *Environment Protection Agency* is less confident of that and its studies are therefore continuing. Hydraulic fracturing requires large quantities of water dependent on the properties of the shale rock involved. It ranges from 10,000–30,000  $m^3$  of water per fracking operation or well [36,37]. There has consequently been a lot of publicity in the UK about the large amounts of water used during the fracking process. The primary water demand is for the initial hydraulic fracturing process and each subsequent fracturing step, suggesting periods of high water demand, which could put temporal stresses on water resources locally [28]. Excessive water use may lead to a fall in the availability of public water supply, ecosystem degradation and adverse effects on aquatic habitats, erosion, and changes in water temperature [36]. But in the UK abstracting water will require a license from the *Environment Agency* (EA) in England [or the equivalent bodies in the other nations of the UK, i.e., *Natural Resources Wales* (NRW) and the *Scottish Environment Protection Agency* (SEPA)]. The abstraction of water resources under stress should therefore be avoided via this licensing process. Some of this water may be recyclable, although it could be contaminated, for example, by *Naturally Occurring Radioactive Material* (NORM). The RS/RAEng report [28] suggests that the latter are found in shales at significantly lower levels than safe exposure limits. However, NORMs only give rise to potential hazard if concentrated in scales, for example, which may be precipitated on pipework. In reality, sea water exhibits higher NORM concentrations than deep saline ground waters in the UK. Nevertheless, wastewaters require careful management and monitoring in order to ensure that NORMs do not become concentrated [36].

In the USA some concern has been expressed over the possibility of methane levels in water that might be high enough to be flammable [38]. It has been asserted by DECC [38] that these are normally caused by failures in the well construction or natural

background levels of methane rather than fracking *per se*. Indeed the RS/RAEng review [28] considered the possibility of direct groundwater contamination to be very unlikely, although it could result from faulty wells. The RS/RAEng review also warned that environmental contamination, including 'faulty wells, and leaks and spills associated with surface operations', were to be expected as they are common to all oil and gas wells and extractive activities. They argued for integrated operational practices [28], such as recycling and reusing wastewaters, to ensure benign water handling and treatment. DECC [38] have put in place a series of requirements to minimise the risk of groundwater contamination from poorly fabricated wells. These include the need for detailed plans to be submitted to the regulator (the EA in England, NRW in Wales or SEPA in Scotland), together with formal risk assessments [35].

US experience suggests that around 40–80% of the injected fracking fluids will be returned to the surface as 'flowback water' [35,39]. This contaminated 'produced water' also poses a potential risk to groundwater once it reaches the surface [37,38]. In the event of human error or equipment failure, it could potentially leak into streams and seep down to the groundwater. However, all drilling pads are double-lined with impermeable membranes and drainage is intercepted. Operators are required to dispose of flowback fluid from wells in a safe manner. Unlike in the USA, this wastewater is not permitted to be stored in open stores or disposed of by borehole injection [28], reducing the risk of this type of environmental incident in the UK. In addition, all fluids on site must be stored in double-skinned (or integrally 'bunded') tanks in case of spills. Similar hazards arise in other industrial processes, and those associated with hydraulic fracturing should be managed appropriately [10,28,40]. Thus, such risks may be 'designed-out' of the system. Fracking chemicals have to be assessed by the relevant regulator on a case-by-case basis.

## 6. Environmental impacts

### 6.1. Local environmental pollution, health and related impacts

There are various local environmental impacts from shale gas fracking: the excessive water use, groundwater contamination and wastewater handling as discussed above, as well as noise, odours, and the disposal of solid wastes. In order to prevent contamination, the integrity of fracking wells must be ensured. Guidelines for achieving this were recommended in the RS/RAEng report [28], which are largely reflected in documents produced by the *American Petroleum Institute* and the HSE that are recommended by DECC [41]. It is believed that properly designed wells should not pose a risk of contamination to underground aquifers [41]. Of course regulation, however good, is ineffective without rigorous enforcement backed by seriously deterrent penalties. Both well design and construction are overseen by an *Independent Well Examiner* and the HSE Wells Inspector. No operation can commence before an inspection by the independent examiner (employed by the operating company or a contractor) who oversees the design, construction and maintenance of a well [42]. However fully independent monitoring of the wells which was recommended by the RS/RAEng report was rejected during the enactment of the UK *Infrastructure Act 2015* [43], primarily leaving the reporting of leakages up to the operating company. Furthermore, the monitoring or management of abandoned wells remains unclear, particularly if an operator becomes insolvent [42].

The (Smith) *Task Force on Shale Gas*, in their second report dealing with local environmental impacts [32], advocated that baseline monitoring of air, land and water should begin as soon as a potential shale gas fracking site had been identified, rather than waiting

for planning permission to drill boreholes is granted. They also recommended that the adoption of the recently mandated US process of 'green completions' or 'reduced emissions completions', whereby the shale gas and associated hydrocarbons is separated from the remaining 'flowback fluid' and the rest of the fluid to be transferred on for further processing, as a compulsory framework for exploratory sites in the UK [32]. This process is claimed to reduce 'fugitive emissions' by around 90%. The TFSG recognised that *green completions* may not be feasible for exploratory wells in Britain, and that some flaring might be required. In that event, operators could convert gas to electricity onsite and link it to the grid as an alternative, more acceptable, option [32].

There are, in addition, aesthetic concerns: visual intrusion of the sort that also results from onshore wind turbine developments. Shale gas fracking requires site operations at the wellhead, as well as the collection and distribution of unconventional gas from the site [44]. Public resistance often focuses on the increased traffic and vehicle exhaust emissions and noise, particularly those emanating from heavy road transport vehicles. Indeed, the first planning application to explore shale gas in the UK was rejected by *Lancashire councillors* [the local authority in that part of the north west of England (see again Fig. 2)] on the grounds of increased noise and visual impact [44]. Drilling often takes place on landscapes of natural beauty that include sensitive wildlife habitats [45]. The *Infrastructure Act 2015* [43] prohibits hydraulic fracturing from taking place in land at a depth of less than 1000 m, whilst ensuring that communities benefit and that the UK has a robust regulatory regime. The UK government had originally "agreed an outright ban on fracking in national parks, sites of special scientific interest (SSI) and areas of outstanding natural beauty" [45], but have subsequently made changes to these exclusion zones arguing that it could hamper this nascent industry. Surface-level fracking operations are prohibited in environmentally-sensitive areas, such as *National Parks, Areas of Outstanding National Beauty (AONB)*, the *Norfolk Broads*, *World Heritage Sites*, and those where groundwater supplies may be at risk [46]. Sites of *Special Scientific Interest (SSI)* will no longer be excluded from the exploration of shale gas under these new terms. These changes were met by significant concern from environmental groups over the risk posed to some of the UK's most important wildlife sites. Operational environmental permits for shale gas fracking in the UK are issued by the EA, NRW, or the SEPA (as appropriate) on a site-by-site basis in line with the requirements imposed in water abstraction licenses, and actual usage monitored over time.

## 6.2. Climate change and fugitive emissions

The 2008 UK *Climate Change Act* [17] set a legally binding target of reducing the nation's GHG emissions overall by 80% by 2050 in comparison to a 1990 baseline. In order to meet this reduction target, the Government's independent *Committee on Climate Change* has suggested that the electricity generation sector will effectively need to be decarbonised by 2030. Gas-fired power stations emit far fewer greenhouse gases per unit of electricity output than coal-fired ones and, for this reason, they are favoured by Helm [47] as a transitional energy option. However, if the UK continues to build and operate gas-fired power stations, the power sector will be locked-in to a fossil fuel technology and unable to decarbonise over the lifetime of these gas-fired power plants unless paired with carbon capture facilities. Unfortunately, the UK Government recently cancelled (on 25 November 2015) their £1bn CCS competition, which suggests that this technology may have an uncertain future in Britain. A CCS option would add extra cost to power generation and also constitute a significant risk of climate change policy failure. Many scientists, policy makers and journalists attributed the 7% reduction in US domestic carbon emissions between 2007 and

2013 to the fuel switch from coal to shale gas. But recent analysis suggested that it in fact only played a small role in this fall, with much of the reduction attributed to the economic recession [48].

Two of the main sources of global warming impact arising from shale gas development are the fugitive methane emissions leaked and vented during extraction processes, and carbon dioxide (CO<sub>2</sub>) emissions from the combustion of the shale gas to produce electricity. Like conventional gas, the primary cause of these GHG emissions result from the combustion of the shale gas in boilers. However, there is a greater variation in fugitive methane emissions from the extraction process, depending on the given location, particularly in terms of enforced environmental legislation. Therefore, much of the controversy over the global warming impact of shale gas technology focuses on such fugitive methane. Methane is a much more powerful GHG than CO<sub>2</sub>, although it resides in the atmosphere for only 12 years [49]. Some of it may be flared (converting it to CO<sub>2</sub>), rather than vented, but this is not or cannot always be done.

The most recent values of *Global Warming Potential (GWP)* for GHGs are provided by the *Intergovernmental Panel on Climate Change (IPCC)* in their *Fifth Assessment Report (AR5)* over three separate time horizons [50]: 20, 100 and 500 year respectively. The application of the three different time horizons are all equally valid for assessing GHGs from a scientific perspective. However, short-lived, more potent GHG emissions have a much higher GWP over the 20 year horizon; consequently methane traps 86 times more heat than carbon over this period, compared to 34 over a 100 year horizon [50]. Some have argued that it might be more pertinent to consider methane emissions over the 20 year horizon to assess the danger it poses to our climate system in the short-term. Nevertheless, the 100 year horizon has been widely used by many, providing a balance between short-term and long-term impact of GHGs on climate change. Furthermore, this is particularly appropriate given that CO<sub>2</sub> accumulates over time in the atmosphere, whereas methane dissipates. Accordingly, the results presented in this assessment of the life-cycle GHG emissions from shale gas are over a 100 year time horizon.

Upstream GHG emissions estimated by several studies have been collated [51–57] in order to explore the potential 'carbon footprint' of UK shale gas (see Fig. 3). The controversial study by Howarth et al. [53] was excluded when averaging this data, because of its relatively high estimates for fugitive emissions. Should rigorous and effective environmental legislation be introduced in the UK, this level of emissions is unlikely to be permitted. Emissions data from the *Ecoinvent* database version 2.2 [58] were used to account for UK NG when generating the latter mix; for both domestic and imported UK fuel routes [from Norway, the Netherlands, the rest of the European Union (EU), and via LNG]. The full

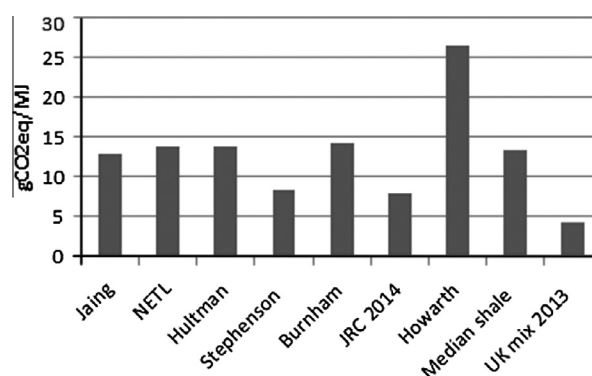


Fig. 3. Central estimates for upstream GHG emissions associated with unconventional gas compared to current UK gas mix.

life-cycle GHG emissions of shale gas electricity generation are compared to the NG generation using the current UK gas mix, LNG and Russian gas respectively in Fig. 4. The LNG emissions data were taken from a review undertaken previously by Hammond and O'Grady [59]. The operational (or 'stack') emissions are based on current UK technology, but may fall over time as more efficient plants come online. Total life-cycle emissions of shale gas generation were estimated to be in the range of 480–546 gCO<sub>2e</sub>/kW h<sub>e</sub>, i.e., 4–18% greater than emissions from the current UK gas mix (with a central estimate of 14% greater GHG emissions). Thus, providing effective regulation to curtail fugitive emissions are in place, electricity generation using shale gas could offer significant savings in carbon emissions when displacing coal-fired generation as part of a transitional energy strategy [59]. This result is in keeping with other estimates found in literature [51,54] and a study carried out by DECC [60], which saw a moderate disparity between conventional and unconventional gas. There are large uncertainties associated with these findings, and they should only be considered as 'indicative' until real operational data are available.

GHG emissions from shale gas are currently higher than that associated with the UK gas mix, although shale gas may offer less GWP than its counterparts as the UK gas supply mix evolves over time, according to Hammond and O'Grady [59]. Over the coming years, both indigenous and European gas supply will decline, leaving the UK more reliant on imports such as LNG and Russian pipeline gas. LNG was found [59] to be 8–26% greater in terms of GHG emissions than the current UK gas mix, while Russian gas was seen to produce 25% higher emissions. These gas supplies from distant regions require long transportation routes through pipelines, which results in high fugitive emissions [61], or they must undergo liquefaction, shipping and regasification: all energy intensive processes that result in additional GHGs being emitted. The development of a UK shale gas industry could decrease the share of these impactful gases in the future UK gas mix, but are likely to impede the penetration of biomethane, which could still result in increased emissions [59]. Similarly, the growth in UK shale gas may provide a cheap supply of gas that could greatly reduce the investment in renewables, and devalue efforts to adhere to carbon budgets.

Sensitivity analysis performed in connection with shale gas studies have shown large ranges in the impact of shale gas, particularly in terms of fugitive emissions and the estimated ultimate recovery per well [62–65]. Hence, without effective regulation (backed by rigorous enforcement and seriously deterrent penalties) to minimise these fugitive methane emission, many of the notional advantages of shale gas may not be realised. An interesting study in the specific context of the Central Belt of Scotland [65] found that significantly greater methane emissions are likely to

arise from shale gas extraction on peatland, in contrast to grassland development typical of the English landscape. However, comparisons between the full chain GHG emissions from conventional and shale gas were taken from the DECC study [60] mentioned above. Legislation to address fugitive methane from shale gas have not yet been specified in the UK, but it is likely that they will be treated in the same manner as fugitive methane from current UK oil and gas production. Consent for venting or flaring in this sector (reserved mainly for maintenance and emergency procedures) must be granted by DECC [66], who are committed to keeping these emissions to a technical and economic minimum. It would be desirable for such 'green completion' techniques, which were also advocated in the second report of the (Smith) *Task Force on Shale Gas* [31], to be mandated during both the explorative and operational phases of the well in order to keep fugitive emissions at an absolute minimum.

The third report of the *Task Force on Shale Gas* (TFSG), published in mid-September 2015, dealt with the climate change impact of shale gas development in the UK [67]. It suggested again that this would be similar to that for conventional gas, provided that the British shale gas sector is "properly regulated" and monitored, and lower than those associated with LNG. They advocated technological innovation and RD&D investment in CCS alongside the extraction of shale gas as a climate change mitigation option. This, they believe, would enable gas to play a transition role in the UK energy mix in the medium-term as advocated by Helm [47] and others [59]. Nevertheless, the TFSG argued that the sector should not prohibit the development of low-carbon energy generation (particularly from renewables), storage and distribution [67]. Just a little after the date that the third report of the TFSG was launched, so too was a review of GHG emissions from conventional and unconventional sources of natural gas over their respective full supply chains [68] by the *Sustainable Gas Institute* (SGI; based at Imperial College London with industrial funding from *BG Group*). These sources included conventional onshore and offshore, shale gas, tight sands, and coal bed methane (CBM). It drew on findings from some 400 papers in order to evaluate the emissions emanating from various extraction, processing and transport routes; albeit mainly based on data from North America. Comparisons were collated between the full chain GHG emissions from conventional and unconventional gas. It found that over the complete range of gas supplies the total GHG emissions associated with electricity generation was 419–636 gCO<sub>2e</sub>/kW h<sub>e</sub> (with a central estimate of 496 gCO<sub>2e</sub>/kW h<sub>e</sub>), which the SGI considered to be well below typical GHG estimates for coal-fired power plants of around 1000 gCO<sub>2e</sub>/kW h<sub>e</sub>. These embrace the range of full chain emissions found from the present study above, although they are obviously much broader than shale gas data. Unfortunately, the SGI figures were not disaggregated in terms of fuel type (e.g., conventional versus shale gas for the current purposes).

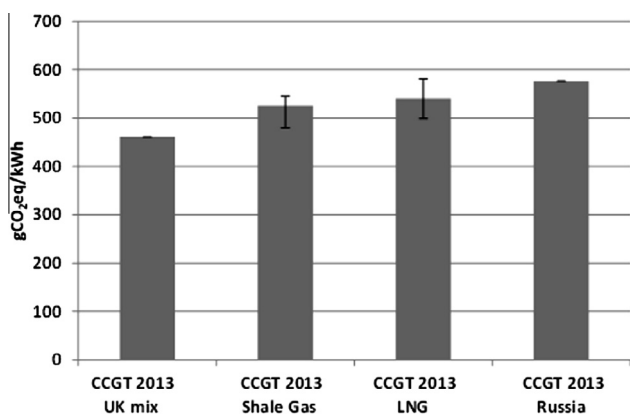


Fig. 4. Life-cycle GHG emissions for gas generation with different gas sources.

### 6.3. Comparing environmental burdens from different life-cycle impact categories

Climate change is the primary focus of most of these studies of shale gas, with little attention given to its wider environmental implications. The first life-cycle assessment was only recently conducted by Stamford and Azapagic [64] but has generated some controversy in the way their results have been represented in the media: as, for example, "fracking trumps renewables" [according to a Media Release by the UK *Institution of Chemical Engineers* in their members' magazine (*The Chemical Engineer*) <http://aboutdatajournalism.org/tcetoday-news-lca-shows-fracking-trumps-renewables/>]. This is because the authors examined a variety of life-cycle impact categories in addition to climate change (for which their central estimate was 462 gCO<sub>2e</sub>/kW h<sub>e</sub>) with varying results between other



environmental burdens. Shale gas was comparable or superior to conventional gas, nuclear power and renewables in terms of the depletion of abiotic resources and eutrophication, as well as freshwater, marine and human toxicities. In contrast, they found shale gas to be more environmentally damaging when photochemical smog and terrestrial toxicity were examined; both, of course, are associated with increased human mortality. Nevertheless, carbon footprints have become the 'currency' of debate in a climate-constrained world [59], where the UK is seeking to dramatically reduce its carbon emissions by 2050. It is therefore of greater significance than these other (important, although perhaps not critical) impact categories. In that regard, shale gas fracking certainly does not "trump renewables".

Stamford and Azapagic's study [64] has attracted other criticisms, including that by Westaway et al. [69]. The latter expressed doubt over some assumptions taken in a UK context in regards to drilling waste disposal, well completion, and the *Estimated Ultimate Recovery* (EUR) of the wells. Westaway et al. argued that Stamford and Azapagic assumed that practices that carried out in the USA, that have long been illegal in the UK (and EU generally), would potentially be used by the shale gas industry in Britain. However, Stamford and Azapagic stressed that the large uncertainties involved in their work was due to the nascent nature of the British shale gas industry. Despite the criticisms, their study [64] demonstrates the high sensitivity of the LCA results to particular parameters of shale gas, reporting large ranges in life-cycle impacts for UK shale gas. It is critical that robust environmental data is collected as an industry grows in Britain, with strong collaboration between operators and the EA.

In view of the early stage of UK shale gas development and of the consequent scarcity of country-specific data, baseline monitoring studies are being planned and undertaken in order to provide GHG emissions and related data over the British supply chain employing airborne, remote sensing, sampling, and sensor network methods. Thus, Allen et al. [70] have obtained and validated trace-gas-concentration and thermodynamic profiles throughout the troposphere and planetary boundary layer using data from aircraft campaigns over and around London. Similarly, Sommariva et al. [71] have taken shale samples from the Bowland-Hodder formation (in northern England) in order to determine, using mass spectrometry, methane and non-methane hydrocarbons (NMHCs). Their results indicate that high temperatures significantly increase the amount of NMHCs released from shale, whilst humidity tends to suppress them. A large fraction of the gas is also released within the first hour after the shale has been fractured. Clearly, much more needs to be done in terms of basic data gathering for real-world hydraulic fracturing operations in the UK. Such data would help reduce uncertainty and allow the potential environmental impact of UK shale gas to be more accurately determined.

## 7. Public and stakeholder engagement

UK Government Ministers have indicated their concern over the fierce resistance to their shale gas fracking policies; particularly from rural communities in both the south and north of England. Potential sites stretch all the way from Dorset to the Kent borders (across the south), via the Bowland-Hodder (in northern England), to at least the Midland Valley of Scotland (see again Fig. 2). There are also potential shale gas reserves in Wales, although there is a relative paucity of data for the Principality. Initial concerns were raised in northern England as a result of induced seismicity caused by exploratory drilling at Preese Hall. Such communities need to be engaged in a two-way dialogue aimed at clarifying the impacts of the shale gas fracking process,

along with its potential costs and benefits. Challenges to energy infrastructural developments in the form of local activism have typically been led by groups, such as the Green Parties (of the nations of the UK) and environmental campaigning organisations, like *Friends of the Earth* and *Greenpeace*, as well as various nature conservation bodies. Public opposition could prove to be a 'show-stopper' for this energy option unless the various stakeholders are engaged in an appropriate consultation. Pigdeon et al. [72] recently examined some of the critical issues concerning the design and conduct of public deliberation processes on energy policy matters of national importance. In order to develop their argument, they employed as an illustrative case study, some of their earlier work on public values and attitudes toward future UK energy system change. They note that national-level policy issues are often inherently complex; involving multiple interconnected elements and frames, analysis over extended scales, and different (often high) levels of uncertainty. It is their view that facilitators should engage the public in terms of 'whole systems' thinking at the problem scale, provide balanced information and policy framings, and use different approaches that encourage participants to reflect and deliberate on the issues. This is similar to what is often referred to as interactive, participatory methods by the technology assessment community [3–5].

DECC has engaged in a process of evaluation of public attitudes to various energy technologies [73], including shale gas fracking. They have commissioned periodic surveys of just over 2000 face-to-face in-home interviews with adults over 16 years of age by specialists from the *Office of National Statistics* (ONS) in a series, or wave, of studies. The most recent (August 2015) survey [73] indicated that around ¼ of the British public were aware of fracking, although only 14% indicated that they knew a significant amount about the process. Of the sample, some 46% were neither supporters nor opponents of extracting shale gas. Those that offered an opinion indicated that around 28% were opposed, whereas 21% supported the exploitation of this technology. DECC have suggested, on the basis of the ONS survey, that support for fracking is related to awareness with 54% of those who claim a lot of knowledge being opposed to the technology (in contrast to 32% in favour of shale gas fracking) [73].

An academic study of UK public perceptions of shale gas fracking by O'Hara et al. [74] has attracted a lot of attention amongst social scientists and policy makers in Britain [37]. It included analysis of policy documents and media sources, semi-structured interviews, and a series of seven nation-wide surveys over the period 2012–2013. The initial survey indicated that 37% of respondents were familiar with shale gas extraction, but this rose to over 60% and then flattened out. This latter phenomenon occurred in spite of a significant increase in media coverage of fracking over this period, particularly via the BBC. O'Hara et al. [74] found that respondents under 25 years of age were least aware of shale gas extraction and its implications. Over 58% of people thought that it would aid energy security, although respondents answered 'don't know' to questions about how shale gas development would impact in terms of climate change. The majority of people who were familiar with the process felt that it should be permitted. Another recent, detailed experimental (online) survey of public perceptions of shale gas fracking in the UK ( $N = 1457$ ) by Whitmarsh et al. [75], included analysis of the effects of different messages on support for, or risk perceptions of, shale gas fracking. They found that the public were generally ambivalent about shale gas, but perceived more risks than benefits. This was strongly influenced by demographic, political and environmental considerations and values. The study [75] discovered that prior knowledge of shale gas extraction had the greatest impact on those respondents who were initially ambivalent or 'undecided', which suggested an important role for information and awareness raising.

The (Smith) *Task Force on Shale Gas* also considered matters around local engagement in their first report [76]. They proposed the establishment of a community engagement plan by operators (albeit with local community involvement) and the full disclosure of information to the local community before an application is submitted to the appropriate regulator. The latter should include logistic and broad site access issues [76], such as the likely number and size of transport movements over the life of a potential drill pad. The *British Geological Survey* has been involved in practical activities associated with public engagement about shale gas fracking [Dr. Robert Ward, BGS, UK, private communication 06.11.15]. They have advocated interaction much in line with that recommended by TFSG [76] although, in addition, the BGS stress the need to utilise tailor-made approaches for different areas/groups, as well as the importance of keeping “information up-to-date, fresh and understandable”. Further elaboration of such surveys, employing the deliberative framework proposed by Pigdeon et al. [72], might go some way towards securing better awareness and understanding of hydraulic fracturing by the public in general.

## 8. Planning, regulation and monitoring

One set of issues for which politicians of different persuasions and community groups agree on is the important need for adequate measures in the area of unconventional gas planning and regulation. Nevertheless, it has yet to be determined whether what community groups consider ‘effective regulation’ will be accepted and upheld by the government. For instance, many local groups are opposed to recent moves by the UK Government to facilitate planning permission for fracking by preventing landowners objecting to the process taking place under their land [77]. DECC issues licenses to onshore oil and gas operators for exclusive drilling rights, and have listed a long set of pre-drilling approvals that are needed from the various regulators [1]. Operators are required to obtain planning permission from the appropriate UK minerals planning authority (county council or unitary authorities in England and the planning authorities in Scotland and Wales) and seek access to the site from landowners [1].

The *Environment Agency* (EA) in England is currently undergoing a consultation to define new standard permits for onshore oil and gas [78]. The process of applying for permits to drill and carry out preliminary testing of wells would be streamlined by removing public consultation. Although a separate permit for hydraulic fracturing will still be required, this has been seen by many as a move to simplify the process and reduce costs for operators. It has also been argued that prior independent [28,32] evaluations of well integrity should be undertaken before drilling can commence, followed by mandated disclosure of hazardous incidents, ongoing process monitoring and contamination assessments. *Public Health England* (PHE) [79], for example, have recently proposed that baseline environmental monitoring be instigated in order to facilitate the impact assessment of shale gas extraction on the environment and public health, that the fracking chemicals (including NORMs) should be publicly disclosed and their risks assessed before use, and that the type and composition of the extracted gas should be determined on a site-by-site basis. This was criticised by a group of medical specialists from the US [80], who argued that it was based on the idea that many of the public health problems experienced in the USA would be replicated in a more densely populated country like Britain. Law et al. [80] suggest that these impacts as yet remain undetermined and require further scientific study using rigorous, quantitative epidemiological methods. However, the UK *Task Force on Shale Gas* [31] generally agreed with the PHE recommendations, but also proposed that the Government should establish a ‘National Advisory Committee’ of independent academic

experts to monitor data from shale gas operations in order to evaluate health impacts.

The TFSG examined planning and regulatory issues in their first report [76]. Their main recommendation was that the UK Government should explore the possibility of creating a new, bespoke regulator for onshore underground energy (unconventional oil and gas, including CBM) that would take over the current regulatory responsibilities of the *Environment Agency* (and its national counterparts), the *Health & Safety Executive*, and DECC. The (Smith) Task Force also suggested [76] that full-scale ‘environmental impact assessments’, which they view as being not easily accessible, should be replaced by ‘environmental risk assessments’ [35]. The TFSG argued [76] that the latter methodology would be “more succinct and approachable” for use by the new regulator in a way that could be made readily available to local communities.

## 9. Concluding remarks

An energy technology assessment (ETA) has been undertaken [3–5,13,14] in order to evaluate the credit and debit ‘columns’ of the shale gas fracking ‘balance sheet’. The adoption of this extraction technology is at a very early stage in the UK with great uncertainty over the scale of the potential shale gas resource. An extensive programme of investigative drilling across the country will therefore be needed in order to provide reliable estimates; possibly requiring hundreds of exploratory wells [20,21]. Nevertheless, the successful exploitation of large-scale development of shale gas extraction in the UK might contribute positively in terms of fuel security and independence, as well as jobs and growth, providing the potentially harmful ‘side-effects’ outlined here can be satisfactorily resolved. But it is unclear whether job creation would be any greater than that arising from equivalent programmes aimed at supporting the adoption of energy demand reduction measures or small-scale low carbon energy options. Similarly, the UK balance of payments would benefit, although it is unlikely that gas bills for household and industrial consumers would fall dramatically as they have done in North America. This is because the UK is part of the wider European natural gas market [23,37] where the gas price is determined by the supply and demand for indigenous natural gas, imports from Russia, and LNG from North Africa. Unconventional gas supplies in the UK will be only a small fraction of those in this wider market. Lessons from the present ETA study will therefore also apply in general across the European Union, albeit tailored by local circumstances.

Hydraulic fracturing requires significant quantities of water which may potentially lead to a fall in the availability of public water supply, ecosystem degradation and adverse effects on aquatic habitats, erosion, and changes in water temperature [28]. However, abstracting water in the UK will require a license from the *Environment Agency* (EA) in England [or the equivalent bodies in the other nations of the UK, i.e., NRW and SEPA]. The abstraction of water resources under stress should therefore be avoided via this licensing process. Recycled fracking fluid could be used for ongoing fracking operations [35,36], except that a proportion of this is not recovered. In the USA some concern has been expressed over the possibility of methane levels in water that might be high enough to be flammable. It has been asserted by DECC [38] that the high methane levels found in some US drinking water supplies were caused by failures in the well construction or natural background levels of methane, rather than fracking *per se*. They have put in place minimum requirements to avoid groundwater contamination from poorly fabricated wells. Fracking chemicals have to be assessed by the appropriate regulator (EA, NRW or SEPA) on a case-by-case basis [79]. Operators are required to dispose of ‘flowback fluid’ from well in a safe manner.

The life-cycle carbon footprint of shale gas has been shown to be lower than that of coal-fired power generators providing stringent regulation is implemented to minimise fugitive methane emissions. On the other hand, the life-cycle carbon footprint was found to be slightly higher than conventional gas, and considerably higher than nuclear power and renewables. It could therefore form part of a transitional UK energy strategy [47,59], although this might jeopardise the attainment of a low (near zero) carbon transition pathway by 2050. The penetration of shale gas into the UK energy mix would likely lead to the lock-in of gas-fired power generation for some decades. Furthermore, without the large-scale use of *carbon capture and storage* (CCS) [81], such a transition would be incompatible with meeting legislated carbon budgets and limiting GHG concentrations to a 'safe' level [82].

The socio-economic benefits and costs of shale gas fracking are not evenly distributed between various communities and demographic groups. Thus, the UK overall might benefit from improved energy security and reduced balance of payments, whilst it will be local communities that bear any adverse environmental and health risks of fracking. Induced seismicity caused by the injection of fracking fluid into and along faults that are already under stress can lead to minor earthquakes or surface tremors. DECC have introduced a set of requirements for new controls, permissions and risk assessments on fracking operations in 2012, based on a 'traffic light' system [27–29] to monitor unusual seismic activity. However, several prominent UK earth scientists have argued [30,31] that future fracking activities in the UK are only likely to cause 'minor damage'; yet again, provided a robust regulatory framework is put in place. Local environmental impacts are critical to neighbouring communities near the wellhead. They focus on shale fracking site operations, as well as the collection and distribution of unconventional gas from the wellhead [44,47]. Public resistance has been largely concerned about increased traffic, which causes vehicle exhaust emissions and noise [79], particularly those emanating from heavy road transport vehicles. In addition, drilling places environmental burdens on landscapes that are often in areas of natural beauty with sensitive wildlife habitats [47].

In order to draw up an objective and rigorous 'balance sheet' for the fracking of shale gas (or indeed other critical technologies) as part of a national dialogue, it would be desirable to bring together experts from a range of disciplines in order to carry out the necessary ETAs. They would need to interact with national and local stakeholders: 'actors' both large and small. That work should be seen by the wider community as *analysis* and not *advocacy*. The UK Coalition Government, when it came into office in 2010, unfortunately closed down or withdrew funding from a number of independent, 'arms-length' bodies established by government departments (sometimes known by the term 'quasi-autonomous non-governmental organisations', or 'Quangos') who might have been capable of conducting studies of this type. Two such bodies were the *Royal Commission on Environmental Pollution* and the *Sustainable Development Commission*. It is unlikely that the present government would re-establish these organisations, but perhaps a future government might consider establishing an alternative. One model might be the *Office of Technology Assessment at the German Bundestag* (TAB), or the equivalent bodies in the Scandinavian countries [4]. In the present context, a new UK agency might look wider than just the scientific and engineering issues, bringing together the technical with the social science perspectives. The latter would be critically important in obtaining insights from various stakeholder groups. That would guard against unwanted side-effects by identifying them in advance of deployment, and could go some way towards engaging and reassuring the community. Constraints on the exploration for unconventional gas are likely to be as much about public acceptance as they are about the various technical issues [72–76]. Community engagement in a gen-

uinely participative process will consequently be critically important for the adoption of any new energy option [3,4] that might meet the needs of a low carbon future. That is certainly one lesson from the shale gas fracking controversy.

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The authors' names are listed alphabetically.

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