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Shale gas and climate change

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Executive summary

SHALE GAS PRODUCTION HAS REVOLUTIONISED ENERGY MARKETS IN THE US, reducing energy costs and contributing to industrial competitiveness, energy security, and employment. The international impact is already significant. The US Energy Information Administration has initially estimated the world's technically recoverable shale gas resources at over 7,000 trillion cubic feet, or 47% of world conventional resources. Shale gas resources are widely spread across the globe and, not surprisingly, there is great interest in the economic potential for developing shale gas more widely.

Governments will rightly pay attention to the economic potential of shale gas. But they should not yet take its realisation for granted. The jury is still out on whether other countries, with different industrial, regulatory, and geological conditions can emulate the US and achieve similar transformations. Governments will also face challenges in exploiting the perceived—but not yet proven—potential of more plentiful and secure energy supplies in a way that is consistent with national and international climate mitigation goals.

The focus of this paper is on the potentially wide-ranging but as yet uncertain implications of shale gas for climate change. On the positive side, shale gas could displace significant amounts of coal as an energy source in some large emitting economies such as China and Poland. This would have significant mitigation benefits since, provided that methane emissions during production are minimised, when shale gas is burned it is roughly half as carbon intensive for each unit of energy generated.

On the other hand, major government incentives for and investments in shale gas production and gas generation may lock-in significant carbon emissions for many decades to come. They could also impact negatively on innovation in and the development and deployment of the even lower-carbon options, including nuclear power, renewables and energy efficiency, required to limit climate risks. To some extent this danger is already evident in energy policy debate in the UK.

Provided that these risks are addressed, shale gas development will not necessarily represent a negative for climate mitigation over the next two decades, and could be positive, particularly if it significantly reduces the use of coal globally.

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In the longer term, the room for gas unabated by carbon capture and storage (CCS) will narrow sharply, particularly in the developed world, if we are to limit the risks from climate change. Major shale gas industries, which may develop in many parts of the world, with associated infrastructure and investment, would be expected financially to have lives much longer than just a couple of decades.

There is, therefore, a vital and urgent need to demonstrate and then deploy CCS for gas power plants (and eventually for industrial uses) if the development of shale gas as a major new industry is to remain consistent with climate objectives for the longer term.

Introduction

Rapid growth in shale gas production has revolutionised the US energy economy in recent years. It has reversed the expectation that the US would become a substantial gas importer, reduced gas prices, and enhanced industrial competitiveness. It also promises to create thousands of jobs. Gas bearing shales are well distributed across the globe and, not surprisingly, there is great interest in the potential for developing shale gas more widely.

The direct greenhouse impact of shale gas combustion, producing carbon dioxide and water, should be less harmful than power generation using coal. Properly regulated and managed shale gas can have a lifecycle footprint of approximately half that of coal. By substituting for coal, shale gas has reduced US carbon dioxide emissions, according to official statistics.[1] However, while US coal consumption has weakened slightly since 2007, US coal exports doubled in the period 2009-2012 as shown in Figure 1. Most of these exports go to Europe.[2]

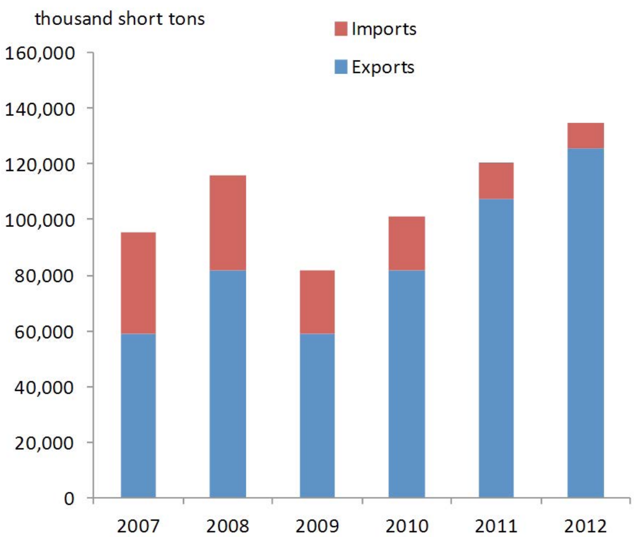


Figure 1: US coal imports and exports (source: US EIA "Quarterly Coal Report January–March 2013"[2]).

However, the process of shale gas exploration and production in the US has also led to substantial methane emissions.[3] This is mainly due to the practice of venting wells to the atmosphere to clear impurities before regular gas production begins ("completion") or after a period of production ("workovers"). Although this venting occurs for only a short period in the production life of the well, these methane emissions have been substantial and, since methane is a more powerful greenhouse gas than carbon dioxide, some have estimated that they may even have been more than sufficient to wipe out the advantage that gas normally enjoys compared to coal in terms of lower climate impact from power generation.[4] However Reduced Emissions Completions (REC) in which methane is recovered rather than vented, are to be made mandatory in the US from 2015.

The global impact on emissions of US (or other) shale gas exploration and production is therefore by no means automatically beneficial.

The shale gas potential of other parts of the world is potentially enormous, but outside the US remains unclear. Estimates published by the US Energy Information Administration (EIA) suggest, however, that shale resources are widely spread across major energy consuming nations and that world *technically recoverable resources* of shale gas may be equivalent to approximately 47% of *technically recoverable resources* of conventional gas.[5] There is, however, great uncertainty as to what share of these resources will ever be commercially recoverable, and on what timetable, since many of the industrial, regulatory and cultural conditions that made the shale gas revolution possible in the US do not exist elsewhere and the geology also varies.

The UK has substantial shale gas resources which could make an important contribution to energy supply if they are technically and economically recoverable. The British Geological Survey (BGS) has estimated that there are 1,329 trillion cubic feet of gas in place in an amalgamation of shale formations across a large area of central Britain but says that it is too soon to estimate how much of this may ultimately be produced.[6] (The BGS study area extends from Merseyside to Humberside and Loughborough to Pickering.) The EIA's initial assessment is that the UK has technically (though not necessarily economically) recoverable shale gas resources of 26 tcf, or about three times its currently proved conventional gas reserves.

While there may be mitigation as well as other significant economic benefits from shale gas in the coming decades, the longer term climate implications of shale gas are potentially far less benign both directly in terms of emissions and indirectly through its impact on energy and climate policies. This briefing paper therefore assesses the likely impact of international shale gas development on efforts to mitigate climate change and what would be required to make the development of this major new industry consistent with climate objectives.

What is shale gas?

Beginning in the 1980s and 1990s, American energy companies perfected techniques for producing natural gas (i.e. methane) from hitherto unproductive rock formations, especially shale. The key technologies are horizontal drilling and hydraulic fracturing; the latter is more commonly known as fracking. Shale gas production has risen rapidly in the US in recent years, reaching 9.6 tcf in 2012, or 40% of US gas production.[5]

Neither the process of horizontal drilling, nor fracking, is a new technology. Both have been used in conventional oil and gas reservoirs, for instance, horizontal drilling played a crucial role in the development of the largest onshore oilfield in the UK, as well as Western Europe, at Wytch Farm in Dorset.[7] But fracking shale is more difficult, because it is stronger and less brittle than more porous conventional reservoir rocks such as sandstone. Only in the last 10 to 20 years have techniques been developed to enable shale to be fracked with confidence.[8]

Impact of shale gas on the US

The shale gas revolution in the US has contributed to spot gas prices that, as of June 2012, are less than a quarter of those in Europe and less than an eighth of those in Asia,[9] with consequent benefits for living costs and industrial competitiveness. Figure 2 illustrates the trends since 2008 and the relationship to oil and coal prices.

It has reversed the previous expectation that the US was to become a substantial gas importer and contributed to a trend towards greater energy independence for the US. President Obama has claimed that hydraulic fracturing could create more than 600,000 jobs in the US by the end of the decade. One consequence has been a decline in coal fired electricity generation in the US which contributed to reducing US carbon emissions in the first quarter of 2012 to their lowest level since 1992.[1]

Environmental and climate concerns

Shale gas plainly has the potential to contribute positively to energy security, affordable energy supply, and industrial competitiveness in many parts of the world. But serious questions have been raised about its environmental impact. There are broadly three issues.

i The impact on the local environment. A report by the Royal Society and the Royal Academy of Engineering[11] concluded that the more likely causes of contamination are faulty wells and leaks and spills associated with surface operations. To a considerable extent this is a question of effective management and regulation.

ii Concerns about methane emissions during shale gas production. Depending, to some extent, on coal and gas qualities, a modern gas fired power station emits somewhat less than half the CO_2 per unit of power generated than a modern coal station. However natural gas (methane) has a much higher global warming potential than CO_2 and this debate is primarily about how much "fugitive" methane escapes to the atmosphere in the course of shale gas production and whether this significantly reduces, or indeed reverses, this advantage over coal (which also has associated methane leakage).[12]

iii Finally, what impact the availability of relatively cheap shale gas in different parts of the world might have on climate change mitigation efforts and, in the UK, on our ability to meet national climate targets.

The focus of this briefing paper is on the second and third of these issues. Local environmental hazards are covered more fully in the Annex.

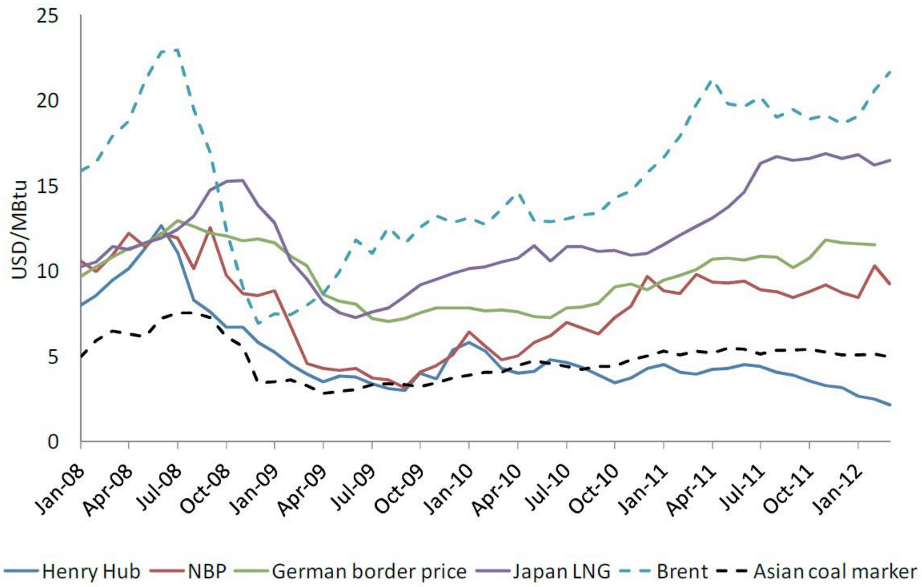


Figure 2: Prices for international gas (2008–2012); Henry Hub is the main US benchmark and the National Balancing Point (NBP) is the UK benchmark (source: IEA "IEA Medium-Term Gas Market Report 2012"[10]).

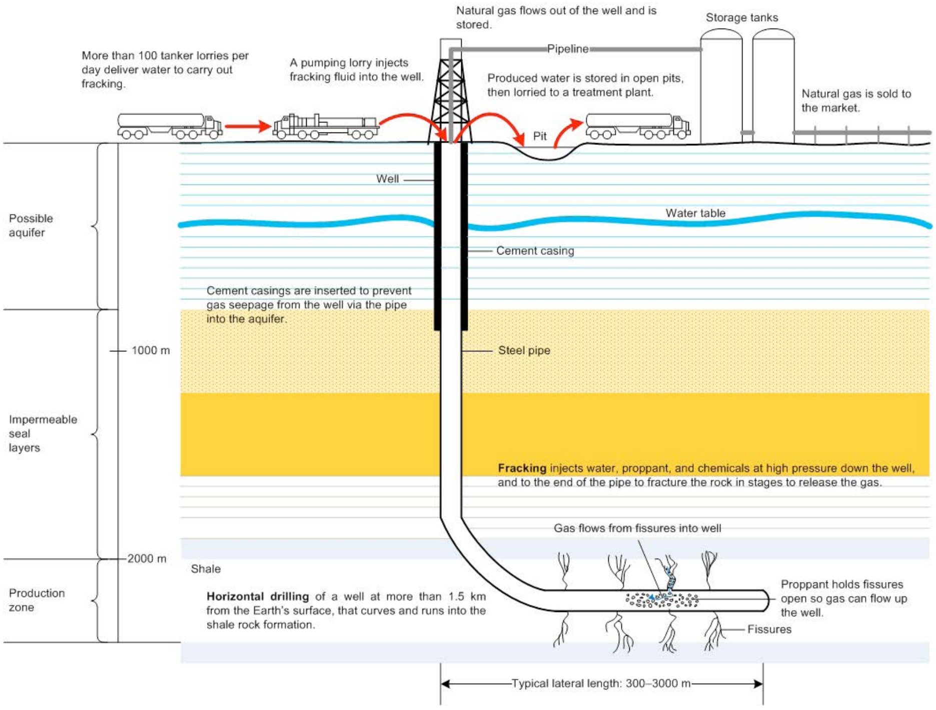


Figure 3: Shale gas operation with fracking (source: adapted from Granberg[14]).

Shale gas technology

Many of the world's most important oil and gas deposits were originally formed in shale, known as the source rock. Some of this oil and gas has migrated underground from the shale into much more porous rocks, such as sandstone. From these formations, the oil and gas can flow relatively easily into extraction wells, and these are the reservoirs of so-called conventional oil and gas production. However much of the oil and gas remains in the shale rock and this is difficult to remove because it is trapped within tiny pore spaces and fixed (or adsorbed) onto clay mineral particles that make up the shale.[13] The use of horizontal drilling combined with fracking has greatly enhanced the ability of producers to extract gas from these structures. Figure 3 depicts a typical shale gas operation with fracking in the US.

The first stage in shale gas production is the drilling of a conventional well that is diverted below ground so as to run horizontally through the shale stratum. As illustrated in Figure 4, the well is lined with a series of concentric casings, which are cemented in. This is intended to insulate the well from the local geology, especially fresh or saline aquifers, and to prevent leakage of gas or liquids from the well or around the outside of the well between strata or to the surface.

The next stage, once the well has been completed is to perforate the well along the section that is within the shale with explosive charges, which is a process not different from conventional oil and gas production. Powerful pumps are then employed to inject the fracturing fluid, which is a combination of water, sand, and chemicals, into the well at pressures sufficient to fracture the shale. The fractures, which normally occur deep below the surface, may extend for a few hundred metres into the rock, and the purpose of the sand and chemicals is to penetrate the fissures and make sure that they stay open.

Before gas production can begin, the pressure in the well is released and between 20-80% of the fluids return to the surface as "flowback". Besides the original fracturing fluids, the flowback may also include water and other materials from the shale stratum containing hazardous metals, hydrocarbons, and naturally occurring radioactive materials (NORM).

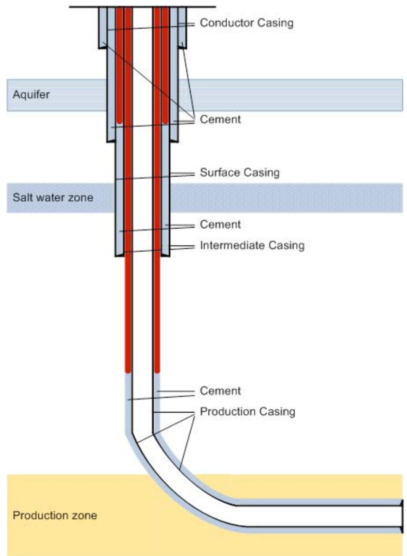


Figure 4: A typical well design for shale gas production (source: redrawn based on Royal Society and the Royal Academy of Engineering[11]).

Greenhouse gas intensity of shale gas production

In certain circumstances the pressure in gas wells has to be released to discharge materials accumulated in the wells—a process called venting. This occurs before regular gas production can begin as part of the well's "completion". It also occurs from time to time over the life of the well during "workovers" to remove accumulated liquids and debris. And if the well is "wet", i.e., it contains some petroleum liquids as well as gas, it may be required from time to time to remove those liquids in a process called "liquid unloading".

In 2010, the US Environment Protection Agency published a document in which it greatly increased its previous estimates of natural gas (methane) released to air, referred to as fugitive methane gas, during these processes. It stated that previous studies had been conducted on the basis of restricted knowledge of industry practices and at a time when methane emissions were not a significant concern in the discussion about GHG emissions.[3]

Methane is a much more potent greenhouse gas than CO_2 but its residence in the atmosphere is far shorter. Based on the Intergovernmental Panel on Climate Change's (IPCC) data, methane has 72 times the global warming potential of CO_2 measured over 20 years but only 21 to 25 times over 100 years.[15]

In April 2011, Howarth et al.[4] published findings, drawing on the new EPA data, which suggested that methane emissions from shale gas production in the US has been so great as to eliminate the climate change advantage of shale gas over coal in power generation, taking the 100-year measure of global warming potential. Further, the paper argued that the GHG footprint for shale gas was "at least 20% greater and perhaps more than twice" that for coal on the 20-year measure. Nevertheless, the paper acknowledged that the uncertainties are large and urged greater investigation. In fact, the issue may not be unique only to shale gas or unconventional gas production in general. Recent studies by researchers mainly based at the US National Oceanic and Administration Earth System Research Laboratory (NOAA ESRL) revealed substantial methane emissions from conventional natural gas wells, and this excluded expected extra emissions mainly from leaks in the pipeline and subsequent distribution stages.[16] A further recent study has revealed high levels of methane leakage at a conventional gas field in Uintah County, Utah.[17] This snapshot study is consistent with other evidence suggesting that official inventory-based estimates of emissions may understate methane emissions.

The Howarth et al.[4] findings have been contested by others. For instance, a subsequent study by researchers at the US Argonne National Laboratory,[18] based in some respects on more detailed analyses of gas field practices, comes to somewhat different conclusions. They find that greenhouse gas emissions arising from shale gas production are actually less than those from conventional gas production. This is largely a result of their assumption that shale gas production is dry and does not require venting for liquid unloading, besides its shorter total lifetime production. On a 20-year basis their central case has shale gas emissions from electricity generation at about 70% of those from coal and on a 100-year basis about 60%.

However on several points, both these studies and other commentators agree. GHG emissions during shale gas development and production make a significant contribution to the lifecycle GHG footprint of shale gas. Even in the Argonne study, on a 20-year measure, these emissions represent more than a quarter of the total. The biggest element is the venting of methane during completions, workovers, and liquid unloading. The data are limited and there is a need for much more thorough study of actual industry practices. Some recent reports, based on local atmospheric pollution analysis in Colorado and Utah, have suggested very high levels of methane leakage that could even exceed those estimated by Howarth et al.[19]

Best practice for greenhouse gas emissions reduction

Reduced emissions completions (REC)—also known as reduced flaring completions or green completions—refer to alternative practices that capture the gas produced during well completions and well workovers under fracking operations.[20] Portable equipment is brought on site to separate gas (mainly methane) from the solids and liquids generated during the high-rate flowback operations. Subsequently, this gas can be delivered into the sales pipeline, hence reducing loss of valuable hydrocarbon resource, on top of reducing emissions of methane, volatile organic compounds (VOC), and hazardous air pollutants (HAP) during well cleanup. In essence, REC enables gas recovery rather than venting or flaring and, in so doing, reduces the environmental impact of shale gas production, as has been found in a recent study.[21] Success stories have been reported by the US EPA Natural Gas STAR program[22] of participants performing REC that recovered much of the gas normally vented or flared during the well completion process and capturing the gas for sale. In these cases the cost of renting the REC equipment was offset by the additional revenue derived from selling the gas. The economics are improving as this technology is being perfected and becoming commonplace, and as its costs decline. It is noteworthy that permitting schemes requiring REC have been implemented in the US state of Wyoming since 2004,[23] and EPA has made such practices mandatory in the US beginning 2015.[11]

Pertinent measures for GHG reduction in shale gas production include giving top priority to well integrity in its design, construction, and abandonment;[11] using low-carbon energy sources in place of the diesel fuel presently used in pumps, compressors, and transportation;[23] and installing onsite processing equipment with technology aimed at obviating or minimising leaks.[24] A recent International Energy Agency (IEA) publication titled "Golden Rules for a Golden Age of Gas" advocates seven principles of best practice for governments, industry, and other stakeholders to responsibly undertake production of shale gas or unconventional gas in general (see Table 1).[24]

1. Measure, disclose & engage
2. Watch where you drill
3. Isolate well & prevent leaks
4. Treat water responsibly
5. Eliminate venting, minimise flaring & other emissions
6. Be ready to think big
7. Ensure a consistently high level of environmental performance

Table 1: Seven principles of best practice for shale gas production advocated by IEA (taken from IEA "Golden Rules for a Golden Age of Gas"[24]).

A recent study prepared for the UK government concluded that if adequately regulated particularly by means of REC, local greenhouse gas emissions from shale gas operations should represent only a small proportion of the lifecycle GHG footprint of shale gas in power generation, which the report estimates as about half that of coal and less than that of imported Liquefied Natural Gas.[25]

Energy demand and mitigation

World primary energy demand grew by 45% between 1990 and 2010 and, according to the International Energy Agency's (IEA) New Policies Scenario,[9] is likely to continue to grow strongly through the rest of this century driven by projected population and economic growth (see Figure 5).

The New Policies Scenario reflects broad policy commitments and plans already announced by countries, including national mitigation pledges and plans to phase out fossil-energy subsidies, even if the implementing measures have yet to be identified or announced. It is not consistent with a policy aim of limiting global mean surface temperature increases to 2 degrees Celsius (2°C).

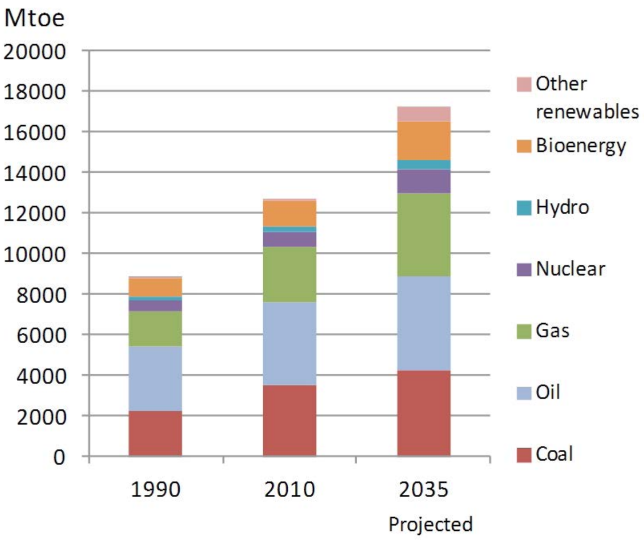


Figure 5: Composition of total primary energy demand (TPED in Mtoe) (source: IEA "World Energy Outlook 2012"[9])

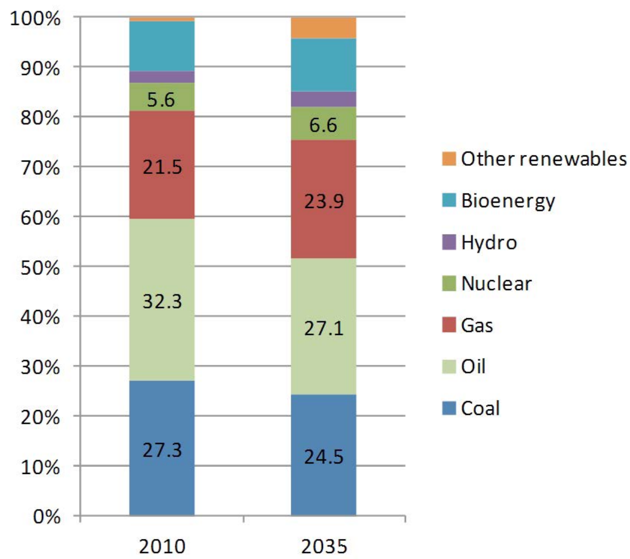
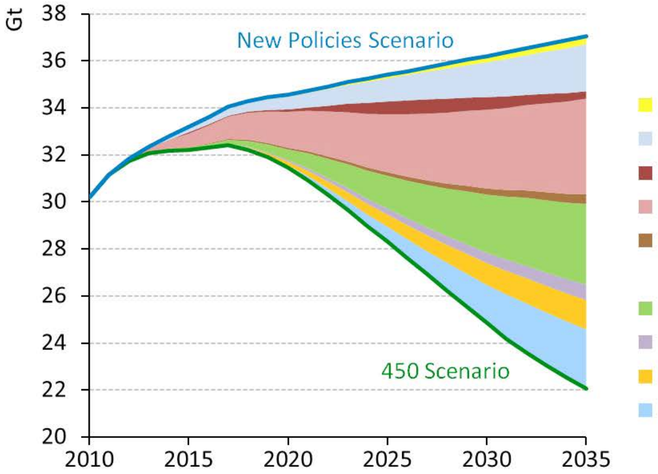


Figure 6: Projected change in composition of total primary energy demand in the IEA's New Policies Scenario (2010-2035) (source: IEA "World Energy Outlook 2012"[9]).

In this scenario, although total consumption of each of the major fossil fuels, coal, oil, and gas increases, the shares of coal and oil are expected to decline, while only that for gas increases (see Figure 6). This scenario for 2035 already includes a major increase in the contribution of unconventional gas from 16% of world gas production in 2011 to about 26% in 2035.

The net result is an increase in carbon dioxide emissions from 30.2 Gt CO_2 in 2010 to 37 Gt CO_2 in 2035, an increase of 20% over the period. This is a much higher level of emissions than in the IEA's 450 Scenario which is broadly consistent with an end of century rise in the global mean surface temperature of 2°C. In that scenario, 2035 emissions fall to 22 Gt CO_2 (see Figure 7). The figure shows the large contributions that will need to come from improved demand and supply side efficiency, renewables, CCS, and nuclear power to contain global warming to 2°C.

In practice additional unconventional gas production will not simply substitute for coal. Some will back out more expensive conventional gas developments. It will also, to some extent, substitute for renewables and nuclear power and stimulate additional energy demand, which will increase greenhouse gas emissions. In their 2011 Special Report,[26] the IEA tried to estimate the balance of these effects, as shown in Figure 8. The figure shows that there is indeed a substantial reduction in emissions from coal, mainly in China, but that this is to a considerable degree counteracted by increases in emissions due to reduced renewables and nuclear energy and increased overall energy demand. The net annual reduction in CO_2 emissions is reduced to a relatively modest 160 Mt.



CO_2 Abatement	2020	2035
Activity	2%	2%
End-use efficiency	18%	13%
Power plant efficiency	3%	2%
Electricity savings	50%	27%
Fuel and technology switchi	2%	3%
Renewables	15%	23%
Biofuels	2%	4%
Nuclear	5%	8%
CCS	4%	17%
Total (Gt CO_2)	3.1	15.0

Figure 7: Global energy-related CO_2 emissions in the IEA's New Policies and 450 scenarios (source: IEA "World Energy Outlook 2012"[9]).

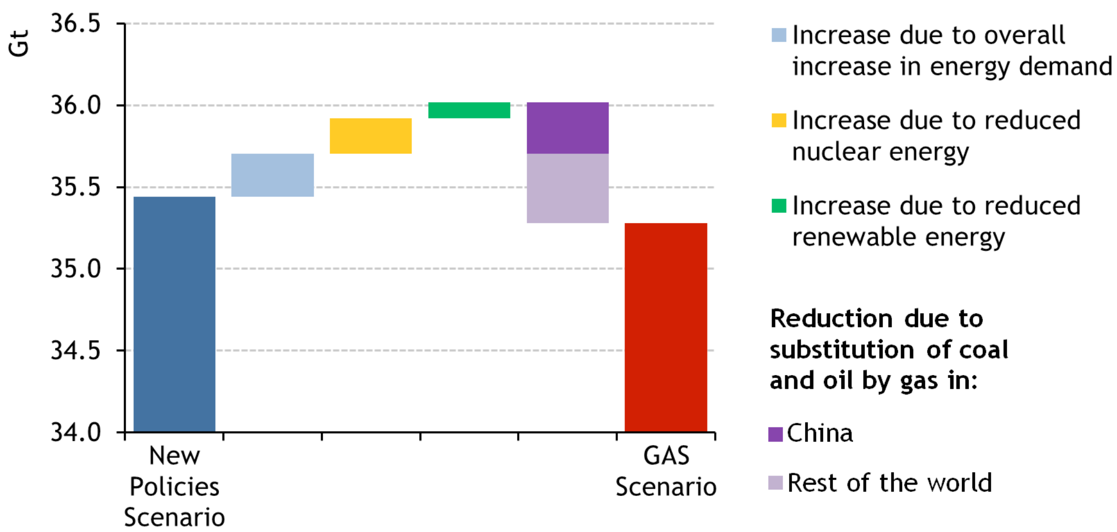


Figure 8: Comparison of CO_2 emissions in the IEA's GAS Scenario to the New Policies Scenario in 2035 according to IEA analysis (source: IEA "Are We Entering a Golden Age of Gas?"[25]).

Longer term studies suggest, however, that by 2050, if we are to meet current climate objectives, then gas in the developed world will mainly be used for power in association with CCS, for "peaking" generation capacity with low utilisation rates, and for relatively hard to substitute uses in space heating and industry.[27]

This leads us to the clear conclusion that without well-developed and proven carbon capture and storage technologies that can be deployed in the late 2020s and early 2030s, expanded fossil fuel use, as exemplified in the New Policies Scenario, will put at risk the achievement of the mitigation goals currently thought to be necessary to avoid the worst of the risks of climate change.

The scenario illustrated in Figure 8 assumes that government support for renewables is maintained and not reduced as a result of the increased availability of gas. However, as the IEA note, "in a scenario in which gas is relatively cheap, there is a risk that governments' resolve in this respect might waiver, pushing gas demand even higher than projected."[25] Changes in the relative price of energy inputs can also impact on the types of technologies that are developed and adopted and recent work on growth and technological change suggests that effectively tackling climate change requires both a price on carbon and policy interventions to direct R&D towards clean technologies.[28] Recently of course, the UK government has launched a consultation on a proposed tax regime for shale gas which the UK Chancellor of the Exchequer has said he wants to "make the most generous for shale in the world."[29]

World shale gas potential

So far shale gas production has been largely confined to North America but, as noted above, recoverable shale gas resources are widely spread across the world. According to initial assessments by the US EIA,[5] the world has 7,299 tcf of technically recoverable shale gas resources, adding approximately 47% to the 15,500 tcf of technically recoverable conventional gas resources. Table 2 shows the ten best endowed countries.

Rank	Country	Shale Gas (tcf)
1	China	1,115
2	Argentina	802
3	Algeria	707
4	U.S.	665
5	Canada	573
6	Mexico	545
7	Australia	437
8	South Africa	390
9	Russia	285
10	Brazil	245
	World Total	**7,299**

Table 2: Top 10 countries by estimated technically recoverable shale gas resources (source: US EIA "An Assessment of 137 Shale Formations in 41 Countries Outside the United States"[5]).

However, as the EIA recognise, all these estimates are uncertain, given the relatively sparse data that currently exists. Technically recoverable resources represent the volumes of gas that could be produced with current technology regardless of prices and production costs and there is great uncertainty as to what share of technically recoverable resources will ever be economically produced, and the timing.

Experience in the US will not necessarily be followed elsewhere in the world. It would certainly take a long time to replicate, elsewhere, the infrastructure of skilled people, drilling and fracturing equipment, and gas pipelines that the US has built up over many years. In many relatively densely populated areas, particularly in the UK and other parts of Western Europe, there may be resistance to the granting of necessary planning consents. As explained in the Annex, it is essential that more rigorous environmental regulation should be imposed and this may increase costs. Also in Europe, for instance, mineral rights generally belong to the state so that, in contrast to the US where they usually belong to land owners, there is little incentive for local residents to encourage development. Other constraints may include the limited availability of water, for instance in many parts of China.

Shale gas potential of Europe, the UK, and China

Europe

The IEA's World Energy Outlook 2012 projects in their New Policies Scenario, that Europe will produce 7.7 tcf of gas in 2035 and import 16 tcf (68% of demand), mainly from Russia, Africa, and the Middle East.[9] Even in the IEA's optimistic case for the potential for shale gas production, Europe remains heavily dependent on gas imports. A recent study published by the European Commission concluded that EU shale gas production would lead primarily to a reduction in imports.[30]

Europe is estimated by the EIA to have 470 tcf of technically recoverable resources with Poland (148 tcf) and France (137 tcf) having much the largest shares.[5]

Poland and France have contrasting shale gas outlooks. Poland has large coal reserves and relies on coal for 90% of its power, while nearly 70% of Poland's gas is imported, mainly from Russia.[31] There is an active drilling programme for shale gas, with major international companies such as Chevron, ConocoPhilips, and Marathon all involved. Shale gas production in Poland is most likely to substitute for Russian gas imports, which would be broadly carbon neutral, or to replace coal for power generation, which could be positive.

France, on the other hand, generates 74% of its power from nuclear stations and only 5% from coal.[32] However France also imports almost all of its 1.7 tcf of gas consumption so there would be considerable scope for France to substitute imported gas with domestic shale gas production. However the current situation is that President Hollande has confirmed an effective ban on shale gas production, citing "the heavy risk to health and the environment" from fracking.[33]

The UK

Drilling for shale gas has been active in the UK since the granting of an exploratory licence to Cuadrilla in 2009. According to the British Geological Survey, the assessment of shale gas resources in the UK is in its infancy. Their latest central estimate of gas in place in one shale gas play across a large part of Britain (Bowland Shale) is 1,329 tcf, but they have made no estimate of how much of this is technically or economically recoverable and they have not updated their previous estimate that the UK's shale reserve potential "could be as large as 150 bcm [5.3 tcf]."[34] The US EIA estimates the UK's technically recoverable shale gas resources at 26 tcf.[5] The US is currently producing a little less than 1% of its technically recoverable shale gas resources (as estimated by the EIA) so, by analogy, perhaps the UK could eventually build its production to 260 bcf. This would be less than 10% of the UK's current gas demand or 20% of gas imports.

Any estimates of eventual UK shale gas production that are made today must be regarded as speculative. Shale gas may have the potential to make a useful contribution to jobs, energy security, and economic growth, but on current estimates it seems unlikely to alter the UK's status as a net importer of gas, at least for several decades. If it simply substitutes for gas imports the effect on greenhouse gas emissions will be broadly neutral.

China

China, the world's largest energy consumer, is estimated to have total recoverable resources of shale gas more than ten times its total recoverable resources of conventional gas. According to the EIA,[5] China has the world's largest technically recoverable shale gas resources, at over 1,000 tcf. China has conducted two licensing rounds, and exploratory drilling is taking place.

In their 2012 publication "Golden Rules for a Golden Age of Gas",[24] the IEA looks at high and low cases for unconventional gas production in China. In the high case (Golden Rules), China produces 13.8 tcf of unconventional gas in 2035, representing 83% of total gas production of 16.7 tcf. In the low unconventional case, unconventional production is 4.0 tcf in 2035, representing 58% of total gas production. About half of the increase in production in the Golden Rules case goes to back out gas imports, reducing gas import dependency from 60% to 20%. The overall cost of gas imports is 60% lower. Since Russia is projected to be China's largest gas supplier probably a large part of this reduction would come from Russian exports. But there is also a major substitution for coal. The net effect is expected to be a reduction of CO_2 emissions of 246 Mt in 2035, i.e., about 2.5% of China's total CO_2 emissions.

Because of the continuing dominance of coal in China's energy sector, the carbon reduction arising from substituting shale gas for coal is likely to outweigh the carbon increases arising where shale gas substitutes for nuclear or renewables or increases energy demand. Realising China's vast shale gas (and, incidentally, also coal bed methane) potential would be of great benefit to China in terms of energy security and competitive energy supply. It could also help to address China's acute problem of air pollution in cities. The development of unconventional gas plays an important part in most low carbon scenarios for China.

Conclusions

Outside North America, the production potential and timescales for shale gas remain uncertain. If shale gas can be developed successfully, in an environmentally acceptable way, there could be considerable economic benefits in many parts of the world, including contributions to energy security and affordability, employment and competitiveness. In much of the developing world increased gas supply could also help to address acute problems of air pollution in cities.

If well-managed and regulated to minimise methane emissions and other more localised impacts, shale gas can potentially also offer mitigation opportunities over the next couple of decades. However without such measures, not yet fully achieved in the US, shale gas may not offer significant advantages over coal in terms of greenhouse emissions and global warming.

Governments will rightly pay attention to this potential. But they should not yet take its realisation for granted. Governments will face challenges in exploiting the perceived—but not yet proven—potential of more plentiful and secure energy supplies in a way that is consistent with national and international climate mitigation goals. Specifically, large scale exploitation of shale gas could impact negatively on the pace and scale of development of the even lower carbon energy options, including nuclear power, renewables and energy efficiency, required to limit climate risks. To some extent this danger is already evident in energy policy debate in the UK. Provided that these risks are addressed, shale gas development will not necessarily represent a negative for climate mitigation over the next two decades, and could be positive, especially in countries with a high dependence on coal.

In the longer term, the room for gas unabated by CCS, will narrow sharply, particularly in the developed world, if we are to limit the risks from climate change. Major shale gas industries, which may develop in many parts of the world, with associated infrastructure and investment, would be expected financially to have lives much longer than just a couple of decades. There is, therefore, a vital and urgent need to demonstrate at commercial scale and, if successful, widely deploy CCS if the development of shale gas is to remain consistent with carbon objectives for the longer term.

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Annex

Local environmental hazards of shale gas development and production

This annex provides a summary of a number of other, non-climate-related environmental issues associated with shale gas production.

Pollution of aquifers

The possibility of water pollution is perhaps the issue that has received the widest public attention with regards to shale gas exploration. However, much of the evidence in this matter is anecdotal and a number of studies have cast doubt particularly on whether observed levels of methane are due to shale gas activity rather than natural causes.[35,36,37,38,39] However in December 2011, the US Environmental Protection Agency (EPA) published a draft of its examination of ground water contamination near Pavillion, Wyoming which concluded that after "alternative explanations were carefully considered ... the data indicates likely impact to ground water that can be explained by hydraulic fracturing." In this case, fracking was taking place at depths as shallow as 372 meters, and "at least 33 surface pits previously used for the storage/disposal of drilling wastes and produced and flowback waters are present in the area."[40] Nevertheless, more testing is being conducted, "after an outcry from Wyoming's governor ... and the energy industry."[41]

However in the UK, most aquifers used for drinking water lie within the first 300 metres below the surface, while fracking operations would normally take place at a depth of more than 1.5 kilometres.[42] US data cited by a joint report by the Royal Society and the Royal Academy of Engineering (hereafter referred to simply as the Royal Society report) shows that fractures created by fracking are very unlikely to propagate vertically more than one kilometre. On average fractures propagate far less than that, in the range of 200 to 400 metres. The report concludes that, "upward flow of fluids from the zone of shale gas extraction to overlying aquifers via fractures in the intervening strata is highly unlikely."[11] The same report judges that more likely causes of possible contamination include poor well construction and leaks and spills associated with surface operations.

As shown in Figure 4, best practice in the UK is to have four strings of casing, with at least two (intermediate and production casing) passing through and thereby isolating any freshwater zones. The Royal Society concludes that "the probability of well failure is low for a single well if it is designed, constructed and abandoned according to best practice."[11] Similarly the management of drilling wastes and flowback waters, which may contain toxic materials, is a matter for good management and regulation as with other industries that manage toxic materials.

Fluids for hydraulic fracturing

All but about 1 per cent of the fluid injected in fracking usually consists of water and sand. The remainder, which is intended to ensure that the sand penetrates the cracks effectively and keeps them open, consists mainly of guar, a polymer derived from wheat which would be safe to eat. Toxic substances such as zirconate or titanium have been used in small quantities, but there are many other options and it is quite possible to use only harmless materials.[8] In the UK, the content of fracking fluids has to be disclosed, although this is not always the case in the US.

Earthquakes

In April 2011 earthquakes were reported near Blackpool, in the vicinity of shale gas exploration. Studies have suggested that fracking is likely to have been the cause by reactivating an existing fault.[43] These events were of magnitudes 1.5 and 2.3. According to an educational website of the Department of Geological and Mining Engineering and Sciences at Michigan Technological University, US, there are 900,000 earthquakes of magnitude 2.5 or less per annum.[44] They are categorised as "usually not felt, but can be recorded by seismograph." In the view of the BGS, it is extremely unlikely that seismic events induced by fracking will ever reach a magnitude greater than 3. These are likely to be detectable by few people and are highly unlikely to cause structural damage at the surface.[13] They are also expected to be less intense than earthquakes due to coal mining.[11]

Water use

An entire multistage fracking operation requires an estimated average of 7,500 to 29,000 m^3 of water per well.[23,25] This is used during the exploration and development stage, including the relatively brief fracking process, and not during production. Water sourcing is typically carried out via tanker trucks or pipelines; water may also be taken (or abstracted) directly from surface water or ground water sources in the local surroundings. As such, potential issues that may arise include impacts on local water supplies along with the transportation involved and the subsequent disposal needs for the wastewater generated. Nonetheless, according to a report by the New York State Department of Environmental Conservation (NYSDEC),[45] which authorizes permit issuance for developing the Marcellus Shale (one of US most active shale sites), fracking would result in a marginal increase in freshwater demand; 0.24% of annual water consumption in their case. A study by researchers at the University of Texas at Austin, USA reveals a total of less than 1% of annual state-wide water withdrawals in three major shale gas plays in Texas, although it is cautioned that local impacts vary with competing demands and resource availability.[46] For instance, the development of Barnett Shale has led to increased demand in the densely populated area of Dallas–Fort Worth.

A recent note by the New York State Water Resources Institute concluded that "seen in this context, water withdrawals for hydraulic fracturing appear to be small relative to power plant cooling withdrawals, and similar to (small to medium) public water supply withdrawals that are happening across the [Great Lake States]. While the total volumes of these withdrawals seem manageable, concern remains over where and when these withdrawals will occur, and how they will be regulated."[47]

Such a case is also evident in the context of the UK. Meeting 10% of UK gas demand from shale gas (estimated at 9 bcm/year) requires only about 0.01% of the licenced annual water abstraction for England and Wales in 2010.[23,48] But of course the local share of demand in the South may be greater. We ought not to rule out the potential significant cumulative local impacts of water withdrawals that are carried out continuously from the same resource, which is a concern raised in the same report by NYSDEC.[45]

Blowouts

Blowouts occur when drilling encounters regions of unexpectedly high pressure or where there is poor well management, and they should therefore be rare. Blowouts from shale operations should be less likely than in conventional wells where drilling is into reservoirs with naturally pressured flow. Blowouts are a safety hazard and also an environmental hazard because of the uncontrolled escape of gas and fluids. The oil and gas industry has great experience in techniques for ensuring well integrity, and the Royal Society report has made specific recommendations for well examination and testing.[11]

Local planning issues

Other local impacts of shale gas exploitation, such as those on visual amenity, noise, and traffic during development and well maintenance, will need to be considered through planning procedures. Because unconventional gas resources are less concentrated than conventional gas, the scale of industrial operations needed to extract them is greater. Some have described the experience as "the circus coming to town." For instance onshore conventional fields may require less than one well per ten square kilometres (though well density may increase as fields mature), unconventional fields might need more than one well per square kilometre.[24]

Units

tcf = trillion cubic feet

bcf = billion cubic feet

bcm = billion cubic feet

Mtoe = million tonnes of oil equivalent

Gt = gigatonnes

Mt = megatonnes

References

1. US Energy Information Administration (EIA). US energy-related CO_2 emissions in early 2012 lowest since 1992. *Today in Energy*, dated 1 August, 2012. Available online: http://www.eia.gov/todayinenergy/detail.cfm?id=7350 (accessed on 11 July 2012).

2. US Energy Information Administration (EIA). *Quarterly Coal Report January–March 2013*, 2013. Available online: http://www.eia.gov/coal/production/quarterly/pdf/qcr.pdf (accessed on 16 July 2013).

3. US Environment Protection Agency. *Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry. Background Technical Support Document*. Washington, D.C.: EPA, 2010.

4. Howarth, R. W.; Santoro, R.; Ingraffea, A. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Climatic Change* 2011, *106* (4), 679-690.

5. US Energy Information Administration (EIA). *An Assessment of 137 Shale Formations in 41 Countries Outside the United States*, 2013. Available online: http://www.eia.gov/analysis/studies/worldshalegas/pdf/fullreport.pdf (accessed on 13 July 2013).

6. Andrews, I. J.. *The Carboniferous Bowland Shale Gas Study: Geology and Resource Estimation*. London, UK: British Geological Survey for Department of Energy and Climate Change, 2013. Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/209021/BGS_DECC_BowlandShaleGasReport_MAIN_REPORT.pdf (accessed on 13 July 2013).

7. BP. *BP UK Asset Portfolio—Wytch Farm*. Available online: http://www.bp.com/liveassets/bp_internet/globalbp/STAGING/global_assets/downloads/U/uk_asset_wytch_farm.pdf (accessed on 8 April 2013).

8. Maitland, G. *Personal communication*. London, UK: Imperial College London, 31 July, 2012.

9. International Energy Agency (IEA). *World Energy Outlook 2012*. Paris, France: OECD/IEA, 2012.

10. International Energy Agency (IEA). *Medium-Term Gas Market Report*. Market trends and projections to 2017. Paris, France: IEA, 2012. Available online: http://www.iea.org/publications/freepublications/publication/MTGMR2012_web.pdf (accessed on 16 July 2013).

11. Royal Society and Royal Academy of Engineering. *Shale gas extraction in the UK: a review of hydraulic fracturing*. London, UK: The Royal Society and the Royal Academy of Engineering, 2012. Available online: http://royalsociety.org/uploadedFiles/Royal_Society_Content/policy/projects/shale-gas/2012-06-28-Shale-gas.pdf (accessed on 7 August 2012).

12. Wigley, T. M. L. Coal to gas: the influence of methane leakage. *Climatic Change* 2011, *108*, 601-608.

13. British Geological Society. Shale gas: challenges and opportunities. *Presented at Shale Gas in the UK*, London, UK: BGS, 18 June, 2012.

14. Granberg, A. I. *What Is Hydraulic Fracturing?* ProPublica: New York, 2012. Available online: http://www.propublica.org/special/hydraulic-fracturing-national (accessed on 28 August 2012).

15. IPCC (Intergovernmental Panel on Climate Change). Climate Change 2007: The Physical Science Basis. In *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, 2007.

16. Petron, G.; Frost, G.; Miller, B. R.; Hirsch, A. I.; Montzka, S. A.; Karion, A.; Trainer, M.; Sweeney, C.; Andrews, A. E.; Miller, L.; Kofler, J.; Bar-Ilan, A.; Dlugokencky, E. J.; Patrick, L.; Moore, C. T.; Ryerson, T. B.; Siso, C.; Kolodzey, W.; Lang, P. M.; Conway, T.; Novelli, P.; Masarie, K.; Hall, B.; Guenther, D.; Kitzis, D.; Miller, J.; Welsh, D.; Wolfe, D.; Neff, W.; Tans, P. Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. *Journal of Geophysical Research* 2012, *117*, 19 pp.

17. Karion, A.; Sweeney, C.; Pétron,G.; Frost, G.; Hardesty, R. M.; Kofler, J.; Miller, B. R.; Newberger, T.; Wolter, S.; Banta, R.; Brewer, A.; Dlugokencky, E.; Lang, P.; Montzka, S. A.; Schnell, R.; Tans, P.; Trainer, M.; Zamora, R.; Conley. S. Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophysical Research Letters* 2013, 40, 1–5.

18. Clark, C. E.; Han, J.; Burnham, A.; Dunn, J. B.; Wang, M. *Life-Cycle Analysis of Shale Gas and Natural Gas*. Chicago: Argonne National Laboratory, US Department of Energy, 2011.

19. Tollefson, J. Methane leaks erode green credentials of natural gas. *Nature* 2013, 493 (7430), 12.

20. US Environmental Protection Agency (EPA). *Reduced Emissions Completions for Hydraulically Fractured Natural Gas Wells*. Washington, D.C.: EPA, 2011. Available online: http://www.epa.gov/gasstar/documents/reduced_emissions_completions.pdf (accessed on 23 August 2012).

21. O'Sullivan, F.; Paltsev, S. Shale gas production: potential versus actual greenhouse gas emissions. *Environmental Research Letters* 2012, *7* (4).

22. US Environmental Protection Agency (EPA). *Natural Gas STAR Program*. Available online: http://www.epa.gov/gasstar/ (accessed on 8 September 2012).

23. Broderick, J.; Anderson, K.; Wood, R.; Gilbert, P.; Sharmina, M.; Footitt, A.; Glynn, S.; Nicholls, F. *Shale Gas: An Updated Assessment of Environmental and Climate Change Impacts*. Manchester,UK: Tyndall Centre for Climate Change Research, 2011.

24. International Energy Agency (IEA). *Golden Rules for a Golden Age of Gas: World Energy Outlook Special Report on Unconventional Gas*. Paris, France: OECD/IEA, 2012. Available online: http://www.worldenergyoutlook.org/media/weowebsite/2012/goldenrules/WEO2012_GoldenRulesReport.pdf (accessed 11 July 2012).

25. MacKay, D. J. C.; Stone, T. J. *Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use*. London, UK: Department of Energy and Climate Change (DECC), 2013. Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/237330/MacKay_Stone_shale_study_report_09092013.pdf (accessed 9 September 2013).

26. International Energy Agency (IEA). *Are We Entering a Golden Age of Gas?*. World Energy Outlook 2011 special report. Paris, France: OECD/IEA, 2011. Available online: http://www.worldenergyoutlook.org/media/weowebsite/2011/WEO2011_GoldenAgeofGasReport.pdf (accessed 2 July 2012).

27. International Energy Agency (IEA). *Energy Technology Perspectives 2012: Pathways to a Clean Energy System*. Paris, France: OECD/IEA, 2012. Available online: http://www.iea.org/publications/freepublications/publication/ETP2012SUM.pdf (accessed 11 July 2012).

28. Acemoglu, D.; Aghion, P.; Bursztyn, L.; Hemous, D. The environment and directed technical change. *American Economic Review* 2012, *102*(1), 131–166.

29. HM Treasury and Department for Communities and Local Government. *Shale Gas: Government Unveils Plan to Kick Start Investment with Generous New Tax Breaks*. Available online: https://www.gov.uk/government/news/shale-gas-government-unveils-plan-to-kick-start-investment-with-generous-new-tax-breaks (accessed on 29 July 2013).

30. Joint Research Centre (JRC) of the European Commission. *Unconventional Gas: Potential Energy Market Impacts in the European Union*. JRC Scientific and Policy Reports. Luxembourg: Publications Office of the European Union, 2012. Available online: http://ec.europa.eu/dgs/jrc/downloads/jrc_report_2012_09_unconventional_gas.pdf (accessed 28 December 2012).

31. International Energy Agency (IEA). *2009 Energy Balance for Poland*. Available online: http://www.iea.org/stats/balancetable.asp?COUNTRY_CODE=PL (accessed 21 December 2012).

32. International Energy Agency (IEA). *Electricity/Heat in France in 2009*. Available online: www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=FR (accessed 21 December 2012).

33. Carnegy, H. Hollande rejects shale gas fracking. *Financial Times*, dated 14 September, 2012. Available online: http://www.ft.com/cms/s/0/4c1f55ec-fe5c-11e1-8228-00144feabdco.html#axzz2PKhTX92p (accessed 21 December 2012).

34. UK Department of Energy and Climate Change (DECC). *The Unconventional Hydrocarbon Resources of Britain's Onshore Basins--Shale Gas*. London, UK: DECC, 2011. Available online: https://www.og.decc.gov.uk/UKpromote/onshore_paper/UK_onshore_shalegas.pdf (accessed 28 July 2012).

35. Osborn, S. G.; Vengosh, A.; Warner, N. R.; Jackson, R. B. Reply to Saba and Orzechowski and Schon: Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *P Natl Acad Sci USA* 2011, *108* (37), E665-E666.

36. Davies, R. J. Methane contamination of drinking water caused by hydraulic fracturing remains unproven. *P Natl Acad Sci USA* 2011, *108* (43), E871-E871.

37. Saba, T.; Orzechowski, M. Lack of data to support a relationship between methane contamination of drinking water wells and hydraulic fracturing. *P Natl Acad Sci USA* 2011, *108* (37), E663-E663.

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38. Molofsky, L. J.; Connor, J. A.; Farhat, S. K.; Wylie, A. S.; Wagner, T. Methane in Pennsylvania water wells unrelated to Marcellus shale fracturing. *Oil Gas J* 2011, *109* (19), 54-67.

39. Energy and Climate Change Committee. *Shale Gas: Government Response to the Committee's Fifth Report of Session 2010–12*. House of Commons: London, UK, 2011. Available online: http://www.publications.parliament.uk/pa/cm201012/cmselect/cmenergy/1449/1449.pdf (accessed on 7 August 2012).

40. US Environmental Protection Agency (EPA). *Investigation of Ground Water Contamination Near Pavillion, Wyoming*. Draft. Oklahoma: EPA, 2011. Available online: http://www.fossil.energy.gov/programs/gasregulation/authorizations/2012_applications/sierra_exhibits_12_100_LNG/Ex._64_-_EPA_ReportOnPavillion_Dec-8-201.pdf (accessed on 28 December 2012).

41. Frosch, D. In land of gas drilling, battle for water that doesn't reek or fizz. *New York Times*, 2 June 2012. Available online: http://www.nytimes.com/2012/06/02/us/in-land-of-hydraulic-fracturing-a-battle-over-water-pollution.html?_r=0 (accessed on 7 September 2012).

42. Fraser, A. *Personal communication*. London, UK: Imperial College London, 6 March, 2013.

43. de Pater, C. J.; S. Baisch. *Geomechanical Study of Bowland Shale Seismicity: Synthesis Report*. Cuadrilla Resources: Staffordshire, UK, 2011. Available online: http://www.cuadrillaresources.com/wp-content/uploads/2012/02/Geomechanical-Study-of-Bowland-Shale-Seismicity_02-11-11.pdf (accessed on 23 August 2012).

44. Department of Geological and Mining Engineering and Sciences. Earthquake magnitude scale and classes. *UPSeis: An Educational Site for Budding Seismologists*. Houghton, Michigan, US: Michigan Technological University. Available online: http://www.geo.mtu.edu/UPSeis/magnitude.html (accessed on 12 July 2013).

45. New York State Department of Environmental Conservation (NYSDEC). *Revised Draft Supplemental Generic Environmental Impact Statement on the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing to Develop the Marcellus Shale and Other Low-Permeability Gas Reservoirs–Executive Summary.* New York: NYSDEC, 2011. Available online: http://www.dec.ny.gov/docs/materials_minerals_pdf/rdsgeisexecsum0911.pdf (accessed on 9 July 2012).

46. Nicot, J. P.; Scanlon, B. R. Water use for shale-gas production in Texas, US. *Environ Sci Technol* 2012, *46* (6), 3580-3586.

47. New York State Water Resources Institute (WRI). *Gas Wells: Water Withdrawals for Hydraulic Fracturing*. Available online: http://wri.eas.cornell.edu/gas_wells_water_use.html (accessed on 19 November 2012).

48. Ward, R. Can shale gas be extracted safely? Groundwater, well integrity, use of water. *Presented at Shale Gas in the UK*, London, UK: BGS, 18 June, 2012.

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