Life Cycle Sustainability Assessment of Shale Gas in the UK

A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Science and Engineering

2017

Jasmin Cooper

School of Chemical Engineering and Analytical Science

Table of Contents

Word count (main text): 61,984

List of Tables

List of Figures

Abbreviations

AADT	Annual average daily traffic flow
AAWT	Annual average weekday flow
ADP	Abiotic depletion potential
AONB	Area of outstanding natural beauty
AP	Acidification potential
API	American petroleum institute
BAT	Best available technology
BEIS	Department for business, energy and industrial strategy
BGS	British geological society
BP	British petroleum
CAP	Vehicle capacity
CCaLC	Carbon calculations over the life cycle of industrial activities
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CFC-11	Tricholorofluoromethane
CML	Centrum milieukunde Leiden, Environmental centre Leiden
CRF	Congestion reference flow
DC	Dual carriageway
DCB	Dichlorobenzene
DE	Direct employment
DECC	Department of energy and climate change
DFS	Diversity of fuel supply
DR	Direct weighting
EA	Environment agency
EIA	U.S. energy information administration
EP	Eutrophication potential
EPA	U.S. environmental protection agency
EU	European Union
EUR	estimated ultimate recovery
EVF	Exponential value function
FAETP	Freshwater aquatic ecotoxicity potential
GaBi	Ganzheitliche bilanz, holistic balance
GDP	Gross domestic product
GE	Gender equality
GEMIS	Global emission model of integrated systems
GHG	Greenhouse gas emissions
GNI	Gross national income
GREET	The greenhouse gases, regulated emissions, and energy use in transportation
GWP	Global warming potential
HGV	Heavy good vehicles
HSE	Health and safety executive
HTP	Human toxicity potential
IEA	International energy agency
INEOS	Inspect ethylene oxide specialities
ISO	International organization for standardization
LCA	Life cycle assessment

LCC	Life cycle cost
LCI	Life cycle inventory
LCIA	Life cycle inventory assessment
LCOE	Levelised cost of electricity
LHV	Lower heating value
LNG	Liquefied natural gas
LUC	Land use change
LVF	Linear value function
MADA	Multi-attribute decision analysis
MAETP	Marine aquatic ecotoxicity potential
MAUT	Multi-attribute utility theory
MCDA	Multi-criteria decision analysis
MODA	Multi-objective decision analysis
NEEDS	New energy externalities development for sustainability
NGO	Non-government organisation
NORMs	Naturally occurring radioactive materials
O&M	Operation and maintenance
OBM	Oil based mud
ODP	Ozone depletion potential
ODS	Ozone depleting substances
PEMEX	Petróleos Mexicanos
PkD	Directional split of peak hour flow
PkF	Proportion of daily traffic flow during peak hour
POCP	Photochemical oxidant creation potential
ppm	Parts per million
PSI	Public support index
PV	Photovoltaic
R&D	Research and development
ReCiPE	RIVM and Radboud University, CML and PRé
SAC	Special areas of conservation
SCGT	Single cycle gas turbine
SLCA	Social life cycle assessment
SMART	Simple multi-attribute rating technique
SONRIS	Strategic online natural resources information system
SPA	Special protected areas
tcf	Trillion cubic feet
TETP	Terrestrial ecotoxicity potential
TRACI	Tool for the reduction and assessment of chemical and other environmental impacts
UAP	Urban all-purpose
UK	United Kingdom
UKOOG	United Kingdom onshore oil and gas
UNESCO	United Nations educational, scientific and cultural organisation
US	United States
VOCs	Volatile organic compounds
WBM	Water based mud
Web-HIPRE	Web HIerarchal PREference
WI	Worker injuries

Life cycle sustainability assessment of shale gas in the UK

Jasmin Cooper, The University of Manchester, 2017

Submitted for the degree of Doctor of Philosophy

Abstract

This research assesses the impacts of developing shale gas in the UK, with the focus of determining whether or not it is possible to develop it sustainably and how it could affect the electricity and gas mix. There is much uncertainty on the impacts of developing shale gas in the UK, as the country is currently in the early stages of exploration drilling and the majority of studies which have been carried out to analyse the effects of shale gas development have been US specific. To address these questions, the environmental, economic and social sustainability have been assessed and the results integrated to evaluate the overall sustainability. The impacts of shale gas electricity have been assessed so that it can be compared with other electricity generation technologies (coal, nuclear, renewables etc.), to ascertain its impacts on the UK electricity mix. Life cycle assessment is used to evaluate the environmental sustainability of shale gas electricity (and other options), while life cycle costing and social sustainability assessment have been used to evaluate the economic and social sustainability. Multi-criteria decision analysis has been used to combine the results of three to evaluate the overall sustainability.

The incorporation of shale gas into the UK electricity mix is modelled in two future scenarios for the year 2030. The scenarios compare different levels of shale gas penetration: low and high. The results show that shale gas will have little effect on improving the environmental sustainability and energy security of the UK's electricity mix, but could help ease energy prices. In comparison with other options, shale gas is not a sustainable option, as it has higher environmental impacts than the non-fossil fuels and conventional gas and liquefied natural gas: 460 g $CO_{2\text{-Eq.}}$ is emitted from the shale gas electricity life cycle, while conventional gas emits 420 g $CO_{2\text{-Eq.}}$ and wind 12 g $CO_{2\text{-Eq}}$. The power plant and drilling fluid are the main impact hot spots in the life cycle, while hydraulic fracturing contributes a small amount (5%). In addition to this, there are a number of social barriers which need to be addressed, notably: traffic volume and congestion could increase by up to 31%, public support is low and wastewater produced from hydraulic fracturing could put strain on wastewater treatment facilities. However, the results indicate that shale gas is economically viable, as the cost of electricity is cheaper than solar photovoltaic, biomass and hydroelectricity (9.59 p/kWh vs 16.90, 11.90 and 14.40 p/kWh, respectively).

The results of this thesis show that there is a trade-off in the impacts, but because of its poor environmental and social ratings shale gas is not the best option for UK electricity. The results also identify areas for improvement which should be targeted, as well as policy recommendations for best practice and regulation if shale gas were to be developed in the UK.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university of other institution of learning.

Copyright statement

Acknowledgement

There are many people who have provided support through the course of my PhD. Firstly I would like to thank my supervisors: Adisa Azapagic and Laurence Stamford, for their guidance. Their words of wisdom since day one have been invaluable and I am truly grateful for the opportunity to work with them on this research. I would also like to thank the other members of the SIS group, whose warmth provided comfort and company throughout the course of my PhD. I am also grateful to the Engineering and Physical Sciences Research Council (EPSRC) who funded this research, as well as the University of Manchester's alumni donors, whose generosity also helped fund this work. I would also like to give additional thanks to the alumni donors who I have met and talked to about my research. Your interest in my work provided a large boost to my confidence, both personally and, most importantly, as a researcher.

Finally, my friends and family have provided much support, encouragement and motivation. I am incredibly thankful to have friends whom I can always turn to, be it a shoulder to cry on or a willing audience to practice presentations on. I would like to thank my parents for their love and support and for keeping my grounded. If it were not for their encouragement during the final year of my undergraduate studies, I may not have applied for this project and could have gone down a completely different career path.

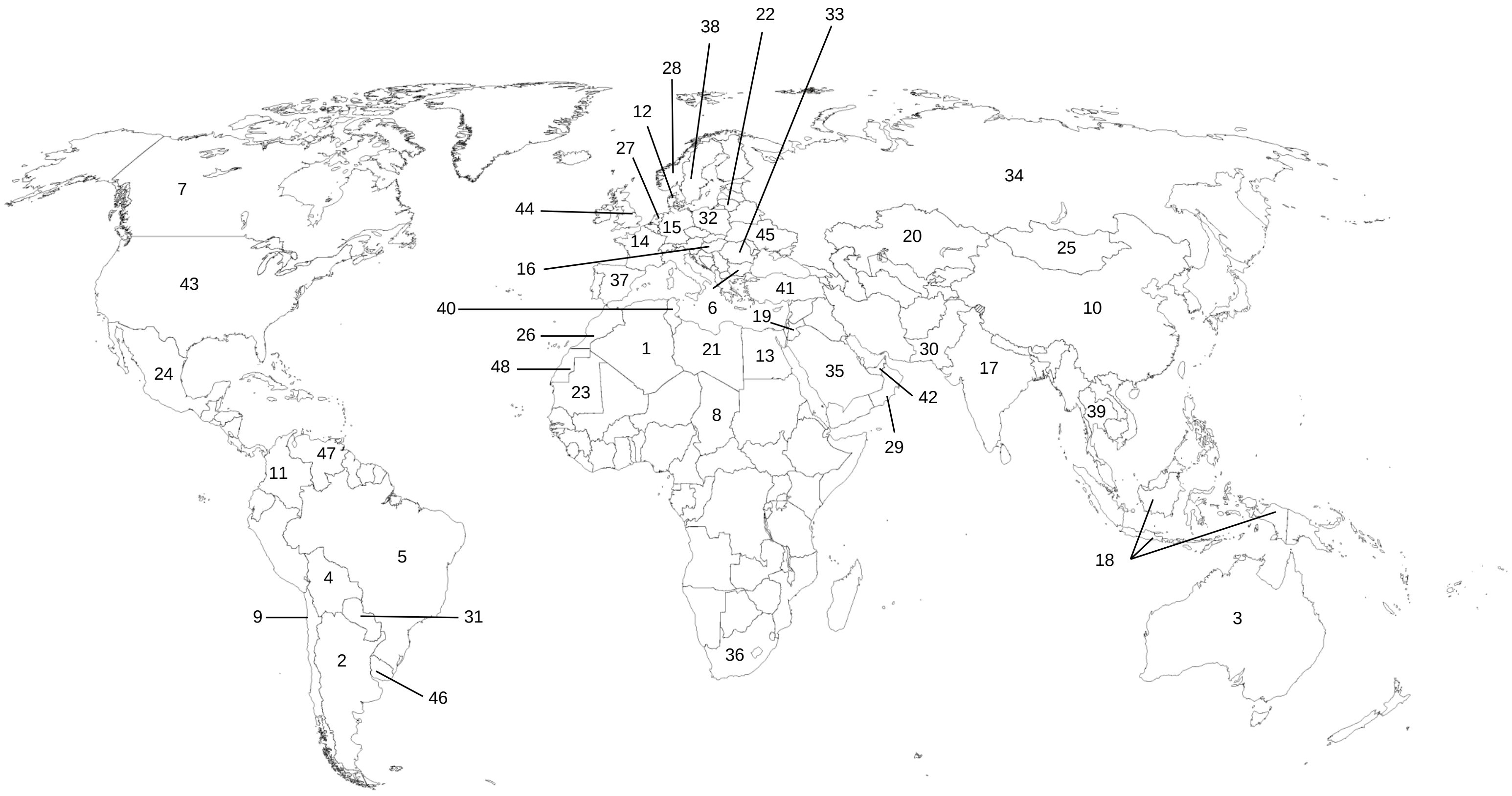
Chapter 1. Introduction

1. Background

Shale gas is natural gas extracted from high porosity, low permeability sedimentary rock deep beneath the earth's surface. Due to the rock from which it is extracted from and the extraction technique required, it is classified as an unconventional gas reserve. The topic is contentious largely due to its environmental and social impacts but it could significantly impact the global energy (and related) sector(s). Its extraction in a way that is sustainable will be key for its future development, especially in countries outside the US. This thesis considers how sustainable extraction in the UK could be, with a focus on its use for electricity generation taking into account various environmental, economic and social aspects. To introduce the topic, the following sections provide relevant background information, followed by the aim of the research and the methodology applied to achieved it.

1.1. <u>Shale gas and how it is extracted</u>

The gas formed from the decay of prehistoric flora and fauna, on which sediment was deposited on top burying it deep underground (Demirbas, 2010; Mokhatab and Poe, 2012). The pressures and temperatures at these depths caused the organic matter to decompose and form natural gas. Both fauna and flora are needed to create natural gas; flora on its own results in the formation of coal while fauna results in oil (Demirbas, 2010). The combination of tectonic movements and changes in sea levels (Figure A1 in Appendix A) are the reasons why natural gas reserves are found both on and offshore. Globally, there is an estimated 6,606.4 trillion cubic feet (tcf) of gas remaining in conventional reserves in 2014 (BP, 2014). The gas extracted from conventional reserves is known as conventional gas; the name derives from how minimal reservoir simulation is needed as the gas is free flowing. Shale gas reserves are estimated at 7,201 tcf (Kuuskraa et al., 2013) and are geographically abundant, with 48 countries identified (so far) to have reserves, as shown in Figure 1 (Huda, 2014; Kuuskraa et al., 2013). The surveying of geology to identify potential deposits is a recent development, so it is possible that in the future more countries could be identified to have reserves (Kuuskraa et al., 2013). An important factor about the location of reserves is that they are located in countries with little or no conventional reserves (Poland and Spain) and countries with depleting conventional reserves (UK, Algeria and Canada) (EIA, 2014). This alone could potentially affect (energy) geopolitics, as over 50% of conventional reserves are located in three countries: Russia, Iran and Qatar, with particular significance to Russia because of relations with Europe (Austvik, 2016; Sherr, 2016).



1. Algeria
2. Argentina
3. Australia
4. Bolivia
5. Brazil
6. Bulgaria
7. Canada
8. Chad
9. Chile
10. China
11. Colombia
12. Denmark
13. Egypt
14. France
15. Germany
16. Hungary
17. India
18. Indonesia
19. Jordan
20. Kazakhstan
21. Libya
22. Lithuania
23. Mauritania
24. Mexico
25. Mongolia
26. Morocco
27. Netherlands
28. Norway
29. Oman
30. Pakistan
31. Paraguay
32. Poland
33. Romania
34. Russia
35. Saudi Arabia
36. South Africa
37. Spain
38. Sweden
39. Thailand
40. Tunisia
41. Turkey
42. United Arab Emirates
43. USA
44. UK
45. Ukraine
46. Uruguay
47. Venezuela
48. Western Sahara

Figure 1: Map of global shale gas reserves. 48 countries identified to have reserves of shale gas (Huda, 2014; Kuuskraa et al., 2013).

Natural gas can be described as either conventional or unconventional (Mokhatab and Poe, 2012). The prior is produced from 'conventional' wells; high porosity, high permeability (1,000 µD) rock, such as sandstone (Stephenson et al., 2011). The latter, on the other hand, is produced from 'unconventional' wells; high porosity, low permeability (≤10 µD) rock, of which shale gas, coal bed methane and tight gas are examples (Mokhatab and Poe, 2012; Stephenson et al., 2011). Another characteristic that differentiates the two is the extraction technique used. Conventional wells do not need to be stimulated in order to produce gas. Conversely, unconventional gas can only be extracted if the well is stimulated (Mokhatab and Poe, 2012). In the case of shale gas, this is carried out by hydraulically fracturing the rock to increase its permeability, in addition to creating a network for the gas molecules to travel through, as illustrated in Figure 2 (Mokhatab and Poe, 2012). Shale gas wells also require horizontal drilling as this increases the surface area of rock exposed, as well as the gas bearing strata being thin (~100 m) (Clark et al., 2013; Mokhatab and Poe, 2012). It should be noted that conventional gas can also be extracted using hydraulic fracturing (increase reservoir productivity) and horizontal drilling (access difficult to reach reservoirs).

To drill a well, the vertical section is first drilled and lined. The well is drilled to a depth of 274 m (900 ft) above the shale layer before turning at an angle to create the horizontal section, as shown in Figure 2 (Clark et al., 2013). The horizontal section cuts through the shale layer, which is typically over 2,000 m beneath the surface (Clark et al., 2013). The top 457 m (1,500 ft) of the vertical section is lined with steel casing and cement, as is the curved and horizontal section (Figure A2 in Appendix A) (MCOR, 2010). The top section consists of three levels of casing: conductor, surface and intermediate, which are for protecting the water table and any deep saline aquifers from being contaminated with fracturing fluid (Koppelmann et al., 2012; MCOR, 2010). The bottom section consists of only one layer of casing and is primarily for controlling fracture formation (Koppelmann et al., 2012). The casing is perforated so that each fracture sequence created stems from a perforation, allowing gas to flow from the rock into the well (Clark et al., 2013; Koppelmann et al., 2012).

The fractures are created by hydraulic fracturing. This involves pumping high pressure fracturing fluid into the well. The fluid pushes its way through the perforations into the rock, creating a network of fractures (Clark et al., 2013; Koppelmann et al., 2012). The fluid used depends on the rock geology, mineralogy and physical properties but typically a mixture of water (90-95 vol%), sand (~5 vol%) and chemical enhancers (<1 vol%) is used (Koppelmann et al., 2012; Montgomery, 2013), commonly referred to as *slickwater* (Montgomery, 2013). The sand acts as a proppant, whose main purpose is to keep the fractures open after hydraulic fracturing has been completed (Montgomery, 2013).

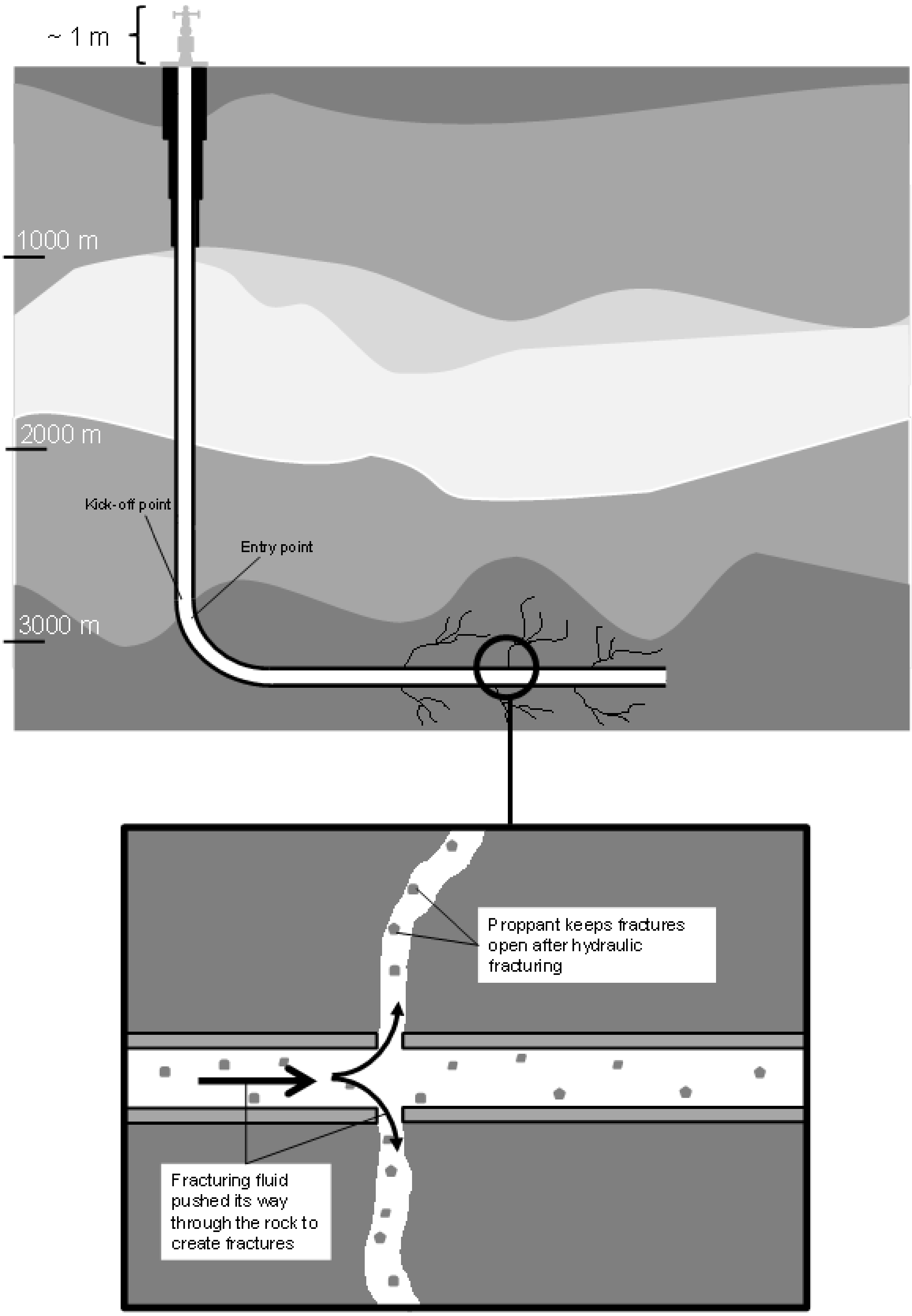


Figure 2: A graphical illustration of shale gas extraction by hydraulic fracturing.

The chemical enhancers improve the fluid's performance, such as friction reducers and stabilisers (Montgomery, 2013). Alternatives to *slickwater* include oil and alcohol based fluids, foams and gels (Montgomery, 2013). Also, polymers, walnut kernels and ceramic particles can be used as proppants instead of sand (Montgomery, 2013; Zoveidavianpoor and Gharibi, 2016). However, *slickwater* is the most commonly used fracturing fluid because of its low cost and effectiveness, despite the high water requirements; 11,000-19,000 m^3 water is required, which is sourced from local water bodies (stream, rivers, lakes and groundwater) (Clark et al., 2013; Freyman and Salmon, 2013; Montgomery, 2013). The well drilling and hydraulic fracturing stages are two of the seven stages required to establish a shale gas well and two of the nine stages in the shale gas electricity life cycle. More details of the life cycle can be found in Section AI.II in Appendix A and Chapter 3.

1.2. Conventional gas and shale gas

Conventional natural gas is one of the main primary fuels used in the world (IEA, 2015b) because it is used by households, industry and for electricity generation (IEA, 2015b). In 2013, gas accounted for 21.4% of global primary energy (coal 28.9%, oil 31.1%, nuclear 4.8% and renewables 13.8%), which is a large growth from 40 years prior when it contributed 16.0% (IEA, 2015b). More significantly, in the same 40 year period, global primary energy consumption has more than doubled from 71,000-157,000 TWh (IEA, 2015b). This rise is largely driven by electricity, for which consumption has grown nearly four-fold (IEA, 2015b). However, the overall electricity mix has changed little since 1973, as shown in Table 1, with fossil fuels accounting for 75.2% of electricity in 1973 and 67.4% in 2013 (IEA, 2015b).

Table 1: Comparison of the global electricity mix in 1973 to 2013 (IEA, 2015b).

Electricity fuel	**1973 (%)**	**2013 (%)**
Coal	38.3	41.3
Oil	24.8	4.4
Natural gas	12.1	21.7
Nuclear	3.3	10.6
Hydro	20.9	16.3
Other renewable	0.6	5.7

Natural gas is a cleaner fuel than coal (and oil), emitting half the CO_2 and insignificant amounts of particulate matter and other pollutants in comparison to coal (Huda, 2014; Kuuskraa et al., 2013; Mackay and Stone., 2013; Tobin et al., 1999). Therefore, it has been suggested that natural gas can be used as a bridge fuel to transition electricity from coal-intensive to low-carbon (IEA, 2011; IEA, 2015a; McGlade et al., 2014).However, natural gas has a finite availability which is relevant to the issue of energy security. As previously mentioned, over 50% of the world's conventional gas reserves are located in three countries. In addition to this, a large percentage of the gas consumed globally is traded (BP, 2014); mostly by trans-country/continental pipelines with a growing percentage as liquefied natural gas (LNG) (BP, 2014). LNG in the context of this thesis refers to conventional LNG; conventional gas which has been liquefied and transported via cryogenic ship instead of transported through gas pipelines. The large quantity of gas traded can result in high gas prices in countries dependent on gas imports. For example, the Asian gas market is highly dependent on imports and consequently the prices are the highest in the world (BP, 2014). Another issue of energy security is dependency of supply. In Europe, four countries (Lithuania, Estonia, Finland and Latvia) are dependent on Russia for all their gas, while nine (Bulgaria, Slovakia, Hungary, Slovenia, Austria, Poland, Czech Republic, Greece and Turkey) rely on Russia for at least 50% of their gas (Lucas and Miller, 2014). In total, some 29 countries in Europe import gas from Russia (BP, 2014; Lucas and Miller, 2014). Therefore, tensions between Russia and EU countries (over Crimea and Syria) and Turkey (which shot down a Russian bomber accused of entering Turkish airspace and the Russian ambassador to Turkey was killed by a Turkish policeman) could threaten gas supplies to most of Europe and put strain on alternative sources such as Dutch and Norwegian gas and LNG (BP, 2014; Girit, 2016; Sherr, 2016).

The above issues are some of the main motivations for developing shale gas exploration outside the US; to increase energy security by easing gas prices and strengthening security of supply. The latter will become increasingly important in the future as electricity consumption is expected to more than double by 2050, because of increasing living standards in developing countries and expected electrification of heating, transport and cooking (DECC, 2010; Frei et al., 2013). Therefore, as conventional gas resources are depleting, shale gas is regarded as an important fuel for meeting future energy needs (Armor, 2013).

Since 2008, the US is the only country extracting shale gas on a commercial scale (Kuuskraa et al., 2013). This is because they were the first country to actively seek out exploiting it, following Federal-funded research into unconventional oil and gas extraction in the 1980s (Litten, 2011; Taylor and Lewis, 2013). However, it was George Mitchell who pioneered its extraction by his use of combining hydraulic fracturing with horizontal drilling in 1999 (Riley, 2013). Since then, the growth of shale gas extraction in the US has been rapid, as can be seen in Figure 3, with a 'boom' in extraction in 2008/2009 (Conti et al., 2013). The US Energy Information Administration (EIA) estimates that by 2040, domestic gas production in the US will reach over 33 tcf, an increase of nearly 40% on 2012 production (Conti et al., 2013). Also, by 2040 shale gas will account for 50% of gas domestically produced (Conti et al., 2013). As a result of the rapid growth in production, the US has shifted from being a net gas importer and in 2016 started exporting gas as

LNG (Crooks, 2016). The US is expected to become a net gas exporter by 2020 (Conti et al., 2015).

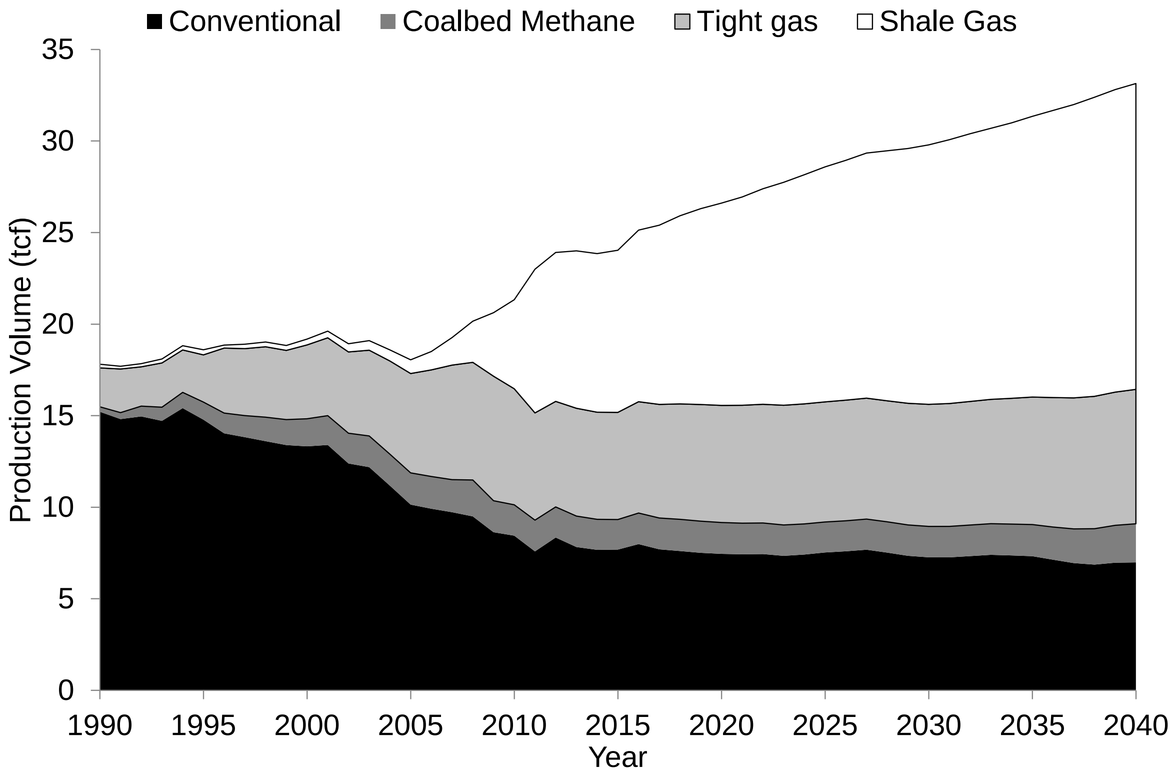


Figure 3: Domestic gas production in the US, historic (1990 to 2012) and predicted (2013 onwards) (Clark et al., 2013).

In addition to this, the growth in gas production has led to a drop in gas prices and greenhouse gas (GHG) emissions from the electricity sector, the latter because the growth in gas production has led to a growth in gas-fired electricity generation, which has replaced coal (EIA, 2013). Also the US chemicals and manufacturing industries are seeing a renaissance, as low gas prices mean manufacturing and chemical production is cheaper than in other countries (PwC, 2011; PwC, 2012). Natural gas is used as a fuel in industry and as a feedstock in the production of fertilisers (ammonia). The by-products of gas extraction, natural gas liquids such as ethane, propane and butane, are also valuable feedstock in the chemicals industry. Ethane, in particular, is essential for the production of ethene/ethylene, which is used in the production of pharmaceuticals and synthetic fabrics (PwC, 2011; PwC, 2012).

Overall, the main motivation for developing shale gas resources is because of the economic success the US has experienced. However, shale gas is a contentious topic, in particular with regards to its impact to the natural environment (Koppelmann et al., 2012). Cases of water contamination and earthquakes caused by hydraulic fracturing activities and the emission of GHGs and other air pollutants are some of the main arguments against its development (Koppelmann et al., 2012; Moore et al., 2014). In the US, cases of water contamination have been found to be the result of wastewater spills and cases of chemical and methane migration to groundwater have been detected (Jackson et al., 2014; Loh et al., 2015; Osborn et al., 2011). Toxic chemicals found in wastewater are a cause for concern to residents living close to well sites, as studies have found illnesses such as headaches and nausea to increase with proximity to well sites (Adgate et al., 2014; Bamberger and Oswald, 2012). This has been attributed to increases in traffic and diesel powered equipment, as well as wastewater pits (Adgate et al., 2014; Bamberger and Oswald, 2012; Brown et al., 2015). In the case of wastewater pits, toxic vapours of chemicals such as benzene are though to have resulted in people living close-by feeling ill (Brown et al., 2015). Furthermore, cases of livestock deaths and birth abnormalities have been recorded on farms close to well sites because of animals drinking water from springs contaminated with wastewater (Bamberger and Oswald, 2012).

Despite the mounting evidence on the harmful effects to people and the environment as highlighted above, countries outside the US are keen to exploit their shale gas reserves in the belief it could boost their energy security. The UK is one of these countries and is currently the most advanced country in Europe regarding shale gas development (Stephenson, 2016). The UK Government wants to encourage exploration because of dwindling North Sea oil and gas production, which has led to the UK being a net importer of gas since 2004 (DECC, 2016). Poland is also keen to develop shale gas but poor test results have led to major investors pulling out (Buckley, 2015; Williams, 2015). Other European countries are also contemplating development, such as Spain, but others, such as France, Germany and Bulgaria, have banned it or have moratoria in place because of environmental concerns (Rosenbaum, 2014; EIA, 2014).

In the long term, the future of shale gas development will depend on whether it can be extracted sustainably, at minimal environmental, economic and social cost. Its future and sustainability implications will also depend on what fuel/energy source it displaces in the energy mix. The following section discusses the latter, focusing on the UK.

1.3. Energy mix in the UK

The UK depends on natural gas for 31% of its primary energy needs and 42% of electricity generated (BEIS, 2017b). The electricity mix has shifted from heavily coal based to be more varied, as shown in

Table 2. Despite this, the electricity mix still contains a large percentage of fossil fuels (53%) and as recently as 2014 28.2% of electricity was generated from coal (

Table 2). The UK Government announced in February 2016 that all coal fired power stations are to be closed by 2025 (Mason, 2015), in order for the UK to meet its legally binding carbon reduction target of 80% by 2050 relative to 1990 (UK Parliament, 2008). However, as coal accounts for a significant fraction of the country's electricity generation capacity, there will likely be a gap in installed capacity.

Table 2: The UK electricity mix between 1980 and 2016 (DECC, 2014; BEIS, 2017b).

Fuel type	1980 (%)	1990 (%)	2000 (%)	2010 (%)	2014 (%)	2016 (%)
Coal	83.4	69.1	30.9	28.1	28.2	8.6
Oil	3.0	6.2	2.5	1.5	1.4	1.7
Gas	0.0	0.1	39.0	47.7	29.2	41.7
Nuclear	12.1	19.0	21.1	15.5	17.1	19.3
Renewables	1.5	1.7	2.7	6.8	18.1	23.5
Imports	0.0	3.9	3.8	0.7	6.0	5.2

The UK nuclear industry is lagging in development, with all currently operating power stations to be taken off line by 2030 and the first new power station not expected to be brought on line (after a delay to construction) until after 2025 (World Nuclear Association, 2016). Also, nuclear power is inflexible, meaning it is good for base load generation but not for meeting peak demand (Elliot, 2007). Solar and wind are intermittent options, so are not well suited for either base load or peak demand generation (POSTnotes, 2014). Hydroelectricity is flexible, making it suitable for both base load and peak generation but schemes are limited to specific locations which have been exhausted (Shiklomanov and Rodda, 2003). Biomass has issues associated with food crop competition and public acceptance and has limited flexibility because dispatch times can be long (Lofthouse et al., 2015; Canadian Electricity Association, 2006; House of Lords, 2008), so it is not ideal for meeting peak demand. On the other hand, natural gas is a flexible electricity source which is quick to bring online (Moniz et al., 2011). In addition to this, it is the UK's largest electricity source, as shown in

Table 2 (DECC, 2014; BEIS, 2017a). Therefore, gas will be important for bridging the electricity mix from high coal to low carbon.

However, as mentioned earlier, the UK is a net gas importer, with 53.6% of gas consumed imported in 2016 (BEIS, 2017a). The imports are from a number of countries (Figure 4), with Norwegian pipeline (65.2%) and Qatari LNG (21.1%) being the biggest suppliers (BEIS, 2017a). Other large suppliers to the UK are Dutch (8.9%) and Belgium (2.9%) pipeline imports. It should be notes that all gas consumed in the UK in 2016 is conventional gas. The large and increasing dependence and volume of imports is the main motivation for developing shale gas in the UK; to alleviate gas import dependence and increase energy security.

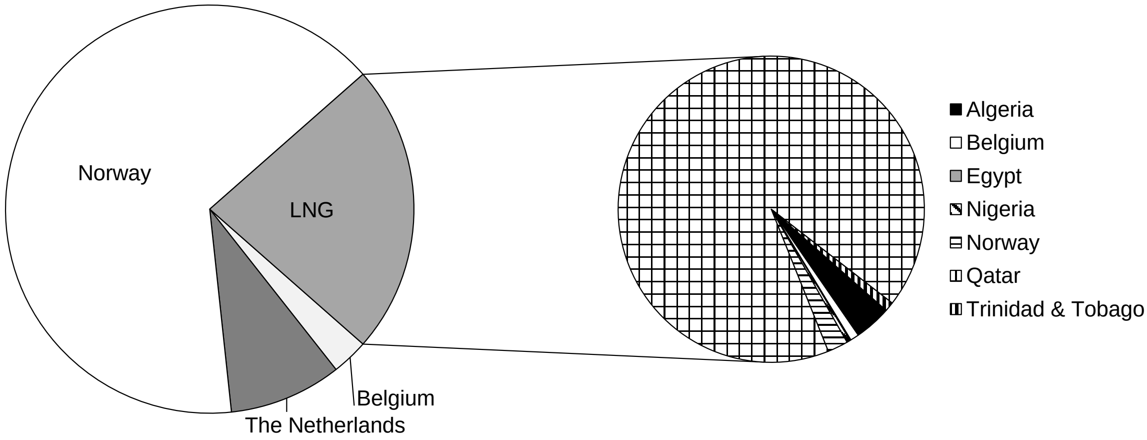


Figure 4: UK gas imports in 2016 by country. Gas imports are either by pipeline (Belgium, The Netherlands and Norway) or as liquefied natural gas (LNG) (BEIS, 2017a).

1.4. UK shale gas

Shale gas development is in the exploration stage in the UK. The British Geological Survey (BGS) estimate that the country could have 1,300 tcf in resources (gas volume in place) (Andrews, 2013). If only 10% is recoverable, it would be enough to meet the country's entire gas requirements for 50 years (based on 2012 consumption) (DECC, 2013d; DECC, 2014), which is another motivation for pursuing shale gas development. Currently development is focused primarily in the Bowland-Hodder shale play. This covers a large area in the north of England, stretching from south of Nottingham to the North Yorkshire Moors and could hold 450 tcf in reserves (gas volume that is recoverable) (Andrews, 2013).

Test well drilling in the UK started in 2010 and since then, a total of six test wells have been drilled, of which one has been hydraulically fractured in Fylde (Preese Hall) (Cuadrilla Resources, 2015; Gosden, 2014; Third Energy, 2016). In August 2017 preparations began for the drilling of the seventh test well, which is also poised to be the second well to be hydraulically fractured (Gosden, 2017). The Government has introduced special tax rates for developers to encourage investment and drilling, as well as setting up a national college to ensure there is no potential skills gap (HM Treasury, 2013; HM Treasury, 2014). However, there is strong opposition to the development of shale gas, both locally and nationally, and progress has been slow in terms of exploration drilling. In the US, over 4,300 wells were drilled in 2012 (Wang and Xue, 2014); over 700 wells have been drilled in China up to 2015; more than 2,100 wells have been drilled in Canada up to

2011 (Becklumb et al., 2015; Oil & Gas 360, 2015). The slow progress in the UK is the result of complex application procedures, involving many permits and stakeholders (DECC, 2013c). The UK Government has recently amended bills to speed up the application process, allowing horizontal drilling below protected sites and giving local councils up to 16 weeks to make decision on applications (Baroness Kramer, 2014; Clark and Bounds, 2015). Whether these amendments will have any impact on the rate of progress is yet to be seen. In addition to this, a charter was established such that local communities will benefit from shale gas extraction (Cronin, 2013). The social and economic impacts from shale gas have been estimated to be modest with regards to job creation, reaching a maximum of 72,000 and capital investment totalling £33 billion (Lewis et al., 2014; Taylor and Lewis, 2013).

In spite of the US's economic success, the impacts of shale gas development and extraction outside the US are uncertain, as is discussed in the next chapter. The degree of transferability of the economic impacts and the effect on the environment in other countries are mostly unknown. This is because no other countries are extracting shale gas on a commercial scale. There has been much speculation from lobbyists about the benefits to the UK economy and employment, but the effects of shale gas on the country are unknown as the UK has no shale gas industry and is years, maybe decades, from establishing a mature industry. Overall, it is uncertain how shale gas development could affect the UK. This is because there have been no comprehensive studies which considered environmental and social concerns alongside economic benefits.

2. Aims and objectives

To address this knowledge gap, the aim of this work is to assess the sustainability of UK shale gas. In particular, the research focuses on shale gas used for electricity generation as a bridge fuel towards a low-carbon energy mix. Taking a life cycle approach, shale gas electricity is evaluated based on its environmental, economic and social sustainability from 'cradle to grave' and compared with other electricity generation options in the UK, such as coal, nuclear power and renewables.

The specific objectives of this work are:

- to assess the life cycle environmental, economic and social sustainability of shale gas production and use for electricity generation;
- to compare shale gas electricity with other electricity options currently available to the UK;
- to assess the impact of shale gas utilisation in power generation on the impacts of UK grid electricity via future scenarios;
- to identify areas of improvement in the shale gas electricity life cycle; and

- to make recommendations for the sustainable production and utilisation of UK shale gas.

As far as the author is aware, this is the first attempt of a full life cycle sustainability assessment of UK shale gas and shale gas in general, integrating environmental, economic and social aspects. The main novelty of this research includes:

- assessment of the environmental, economic and social impacts of shale gas extraction and use for electricity generation, in the UK, on a life cycle basis;
- integration of the environmental, economic and social sustainability using multi-criteria decision analysis to appraise the overall sustainability of shale gas electricity;
- evaluation of the impact of shale gas on the sustainability of UK electricity by developing future scenarios and comparing this with the current grid mix;
- comparison of the overall sustainability of shale gas electricity with other electricity options for the UK, to identify how sustainable it is relative to the other options; and
- identification of areas for improvements in the shale gas electricity life cycle.

3. Thesis structure

This thesis is presented in the alternative format as a collection of five papers which are presented in chapters 2 to 6. Two papers have already been published in the peer-reviewed journal *Energy Technology* (chapters 2 and 3) and the other three (chapters 4 to 6) are pending submission to appropriate journals.

Following the overview of the research methodology in the next section, paper number 1 in Chapter 2, presents a literature review and a critique of the shale gas literature, considering economic, environmental and social aspects. Chapter 3 (paper number 2) presents the results of the environmental life cycle assessment of shale gas electricity in the UK. Here, shale gas is also compared with other electricity options as well as its impact on the current and future electricity mix in the year 2030. The life cycle economic sustainability of shale gas electricity is considered in Chapter 4 (paper number 3) in terms of its competiveness with other electricity options and potential impact on a future electricity market. Chapter 5 (paper number 4) presents the results of the social sustainability assessment, taking into account a range of indicators, including employment, health and safety and energy security on a life cycle basis where applicable. The results of the environmental, economic and social sustainability assessments from papers number 2 to 4 are then integrated in paper number 5 in Chapter 6, to evaluate the overall sustainability of shale gas electricity relative to the other UK electricity options. The final chapter (Chapter 7) summarises the results and conclusions of this work and provides recommendations for the shale gas industry and policy makers, as well as suggestions for future research.

4. Methodology

In this work, a number of steps have been taken to evaluate the sustainability of shale gas production and use for electricity generation; these are shown in Figure 5 and are outlined in the sections below.

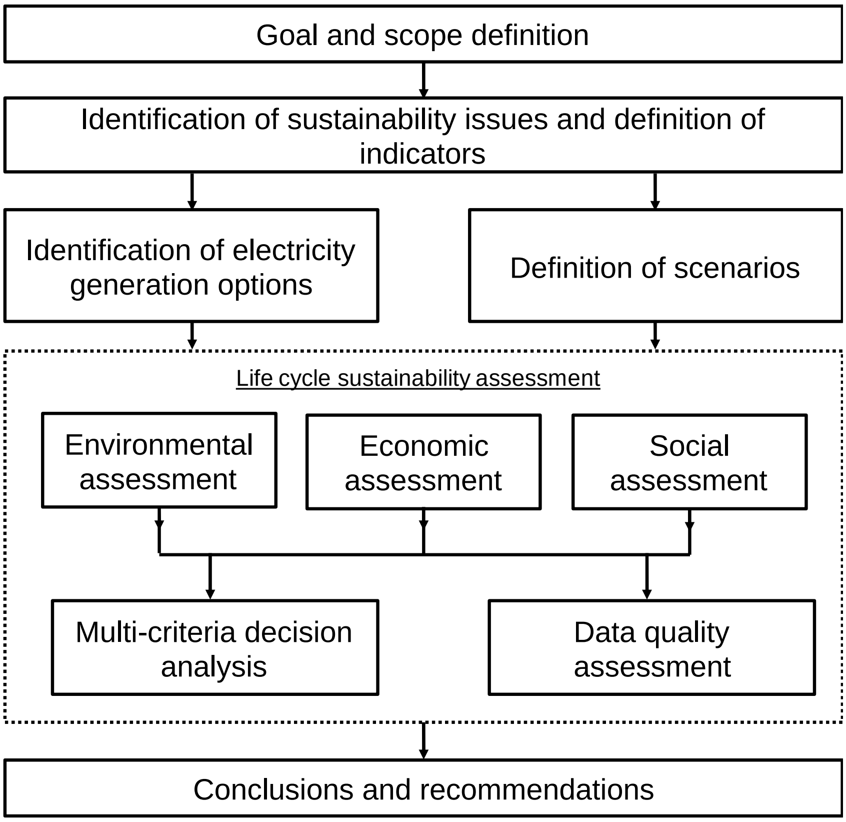


Figure 5: The methodology used for the sustainability assessment of shale gas production and use for electricity generation in the UK.

4.1. Goal and scope definition

The first step in this research is to define the goal and scope of the study. As outlined in Section 2, the goal of the study is to assess the life cycle environmental, economic and social sustainability of shale gas production and utilisation and to integrate these to evaluate its overall sustainability, focusing on the use of shale gas for electricity generation. The scope is from 'cradle to grave'. As the focus is on the generation of electricity, its distribution, transmission and end use are not considered, as shown in Figure 6. A more detailed description of the system boundaries of shale gas and the other electricity options can be found in chapters 3 to 5, as well as in figures A3 to A9 in Appendix A. The functional unit used is the '*generation of 1 kWh of electricity'* in the power plant and it is assumed that the power plant is fuelled with only shale gas. A shale gas well has a production life span of 30 years and the power plant a life span of 25 years. It is assumed that 4,000 shale gas wells will be drilled in the UK over a period of 15 years, with a maximum annual drilling rate of 400 wells. A well refers to a horizontal well. The wells will be situated on well sites called well pads; a well pad contains 40 wells. The well pad will have ten vertical (parent wells) wells drilled, from which each will have four horizontal branches. A well is hydraulically at the beginning of its life and can be re-fractured later on to increase productivity. Hydraulic fracturing of the lateral section of the well occurs in stages; typically 1,000 ft (304 m) at a time (Clark et al., 2013). However, as the option to re-fracture a well (and how many times) is up to the operator and it is uncertain how many times a well will be re-fractured, only one hydraulic fracturing event is considered in this work.

The environmental sustainability assessment has been conducted using life cycle assessment (LCA); the economic sustainability assessment conducted using life cycle costing (LCC) based on levelised cost of electricity; the social sustainability assessment conducted using numerous indicators to assess various impacts to society as a result of shale gas extraction and utilisation for electricity generation. The indicators chosen for these assessments (discussed in more detail in the next section) have been selected as they have been used in previous similar studies or are subjects of interest as highlighted in the literature. The effect of shale gas on the electricity mix (discussed in detail in Section 4.4) has been considered in future scenarios by altering the level of shale gas penetration in the gas/electricity mix.

The system boundary shown in Figure 6 has been used for the LCA, LCC and social sustainability assessment. However, the full system boundary could not be used for all the chosen indicators. For two of the economic indicators, a ‘cradle to gate’ and ‘gate to gate’ system boundary has been used (see Section 4.5.2 for more details). For the social indicators, the full system boundary could not be applied to all the chosen indicators and ‘cradle to gate’ or ‘gate to gate’ system boundaries have been used (see Section 4.5.3 for more details.

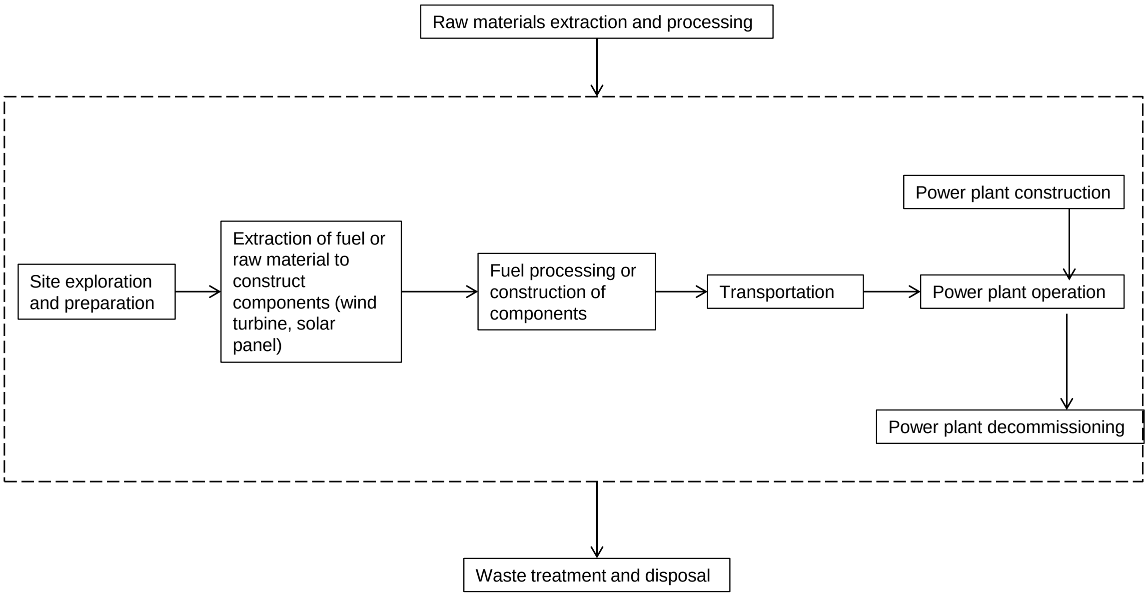


Figure 6: Life cycle system boundary considered for electricity options.

4.2. Identification of sustainability issues and definition of indicators

The next step is to identify sustainability issues relevant to shale gas and to translate these into appropriate sustainability indicators to be used for the assessment of its sustainability. As indicated in Table 3, 11 environmental, three economic and 14 social indicators have been used to address the environmental, economic and social sustainability issues identified in the course of this research. These were identified through available literature, as discussed at length in Chapter 2. The environmental indicators are those typically used in life cycle assessment (LCA), which has been carried out to evaluate the environmental sustainability of shale gas and other electricity options. To estimate the environmental impacts, the CML 2001 (Centrum Milieukunde Leiden, Environmental Centre Leiden) method has been used; comprising 11 indicators which are given in Table 3. This method is one of the most widely used in the LCA literature (Azapagic et al., 2011). The economic sustainability has been evaluated considering the life cycle costs of shale gas and other electricity options; levelised, capital and fuel cost are also considered. These are typical indicators used in evaluating the economic sustainability of electricity options (Mundada et al., 2016; Santoyo-Castelazo and Azapagic, 2014; Stamford and Azapagic, 2012). The social sustainability indicators have been chosen based on the findings of the literature review (Chapter 2) which helped to identify the pertinent social sustainability issues. The environmental, economic and social indicators are discussed further, in the subsections on LCA, LCC and social sustainability assessment. Prior to that, the following two subsections outline the other electricity options and future scenarios considered.

4.3. Identification of electricity generation options

In the third step, alternative electricity options, which shale gas can be compared to, are identified. The UK electricity mix has been used to select the technologies: conventional gas, liquefied natural gas (LNG), coal, hydroelectricity, nuclear power, wind, solar photovoltaic (PV) and biomass (DECC, 2013d; DECC, 2014). It should be noted that conventional gas refers to gas produced domestically in the UK from the UK Continental Shelf. Conventional gas pipeline imports are not considered as the only difference between pipeline imports and domestic gas is the longer transport pipeline. Also, oil used for electricity generation is not included because it contributes less than 2% to grid electricity (DECC, 2014; DECC, 2013a). The system boundaries for each of the options can be found in Chapter 3 and figures A3 to A9 in Appendix A.

Table 3: Sustainability indicators used in this work.

Sustainability aspects	Sustainability issues	Indicators	Units[a]
Environmental	Resource depletion	Abiotic resource depletion (elements)	kg Sb_{-Eq}.
		Abiotic resource depletion (fossil)	MJ
		Acidification potential	kg SO_{2-Eq}.
	Emissions to air, water and land	Eutrophication potential	kg $PO_4^{3-}{}_{-Eq}$.
		Freshwater aquatic ecotoxicity potential	kg DCB_{-Eq}.
		Human toxicity potential	kg DCB_{-Eq}.
		Marine aquatic ecotoxicity potential	kg DCB_{-Eq}.
		Ozone depletion potential	kg CFC-11_{-Eq}.
		Photochemical oxidant creation	kg C_2H_{4-Eq}.
		potential	kg DCB_{-Eq}.
		Terrestrial ecotoxicity potential	kg CO_{2-Eq}.
	Climate change	Global warming potential	
Economic	Costs	Levelised cost of electricity	pence
		Capital cost	pence
		Fuel cost	pence
Social	Employment	Direct employment	Person-years
		Local employment[b]	%
		Gender equality[b]	-
	Health and safety	Worker injury	Injuries
	Nuisance	Noise[b]	dB
		Traffic increase[b]	%
	Public perception	Public support	%
		Media impact[a]	-
	Local communities	Spending on local suppliers[b]	%
		Direct community investment[b]	%
		Diversity of fuel supply	-
	Infrastructure and resources	Wastewater treatment[b]	-
		Land use[b]	-
		Regulatory staff requirements[a]	-

[a] Per kWh electricity generated for all environmental and economic indicators and two social indicators (Direct employment and worker injuries).

[b] Shale gas extraction only.

4.4. Definition of scenarios

Following the identification of electricity options, possible future electricity mix scenarios are defined. The year 2030 has been selected for the future scenarios as shale gas is not expected to reach commercial scale extraction until after 2020 (Lewis et al., 2014). In order to model the 2030 electricity mix and the effects of shale gas resources, the 2030 gas mix is also modelled. For this, two gas mix scenarios are considered: high shale gas penetration (28.4%) and low shale gas penetration (4.5%) (Williams et al., 2011). This allows the impact of shale gas on the electricity mix scenarios to be modelled. The 2012 electricity mix is considered as a baseline because when this project started, data for the 2012 electricity mix was the most recent available. The gas and electricity mix scenarios can be found in chapters 3 to 6.

4.5. Life cycle sustainability assessment

The fourth step in the methodology is the life cycle sustainability assessment, which itself is made-up of five steps. These are outlined in the following sections. Assumptions and data sources are discussed in more detail in chapters 3 to 6, as well as in sections AIII to AVIII in Appendix A.

4.5.1. Environmental sustainability assessment

As mentioned earlier, life cycle assessment (LCA) is used to evaluate the environmental sustainability of shale gas and the alternative electricity options. The LCA has been carried out following the methodological guidelines in the ISO 14040 and 14044 standards (ISO, 2006a; ISO, 2006b). The functional unit is defined as the '*generation of 1 kWh of electricity'* and this is used for all the electricity options and the electricity mix scenarios. The LCA has been carried out using GaBi v.6 software and the CML 2001 impact assessment method (thinkstep, 1992-2016; Heijungs et al., 1992) has been used to calculate the environmental impacts. The impacts calculated are listed in Table 4. For a description of the LCA methodology and details on how the impacts are calculated, see Section AIV in Appendix A. Further details on how LCA has been used for this study, as well as data and assumptions, can be found on Chapter 3, Section AV in Appendix A and Appendix B. The LCA results are presented in Chapter 3, where further details and assumptions can also be found. The full life cycle system boundary has been considered for all the environmental indicators.

Table 4: LCA indicators used to assess the environmental sustainability. Indicators are those calculated using the CML 2001 impact assessment method.

Impact category	**Description**
Abiotic depletion potential (elemental) (ADP_e) Abiotic depletion potential (fossil) (ADP_f)	The depletion of abiotic resources i.e. fossil fuels, metals and minerals, measured in kg antimony equivalent or MJ for fuels.
Acidification potential (AP)	The potential of acid deposition from sulphur dioxide (SO_2), NO_x and ammonia (NH_3) measured in kg SO_2 equivalent.
Eutrophication potential (EP)	The potential of nutrients to cause over-fertilisation of water and soil, measured in kg phosphate (PO_4^{3-}) equivalent.
Human toxicity potential (HTP)	The release into air, water and soil of substances toxic to human health, measure in kg 1-4-dichlorobenzene (DCB) equivalent.
Freshwater aquatic ecotoxicity potential (FAETP) Marine aquatic ecotoxicity potential (MAETP) Terrestrial ecotoxicity potential (TETP)	The release of substances toxic to aquatic and terrestrial environments, measured in kg DCD equivalent.
Global warming potential (GWP)	The potential for climate change is measured by the GWP, which is a measure of the amount of heat trapped by atmospheric greenhouse gases (GHG). The total GWP of the different GHG is measured in kg CO_2 equivalent.
Ozone depletion potential (ODP)	The potential for emissions of ozone depleting substances (ODS) to deplete the ozone layer, measured in kg trichlorofluoromethane (CFC-11 or R-11) equivalent.
Photochemical oxidant creation potential (POCP)	The potential of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) to generate photochemicals or summer smog, measured in kg ethylene equivalent.

4.5.2. Economic sustainability assessment

Life cycle costing (LCC) has been used to assess the economic sustainability of shale gas production and utilisation for electricity generation, as well as to compare it to the other options. The LCC methodology proposed by The Department of Energy and Climate Change (DECC) (DECC, 2013b) has been followed for these purposes. In addition to the LCC, the levelised, capital and fuel costs (cost of shale gas to the power plant or cost of fuel to the power plant) are used to assess the economic viability of shale gas electricity relative to the other options. These indicators have been selected because they have been used in previous energy economic sustainability studies (Mundada et al., 2016; Santoyo-Castelazo and Azapagic, 2014; Stamford and Azapagic, 2012). The economic indicators are defined in Table 5. Further details on the LCC methodology, as well as data and assumptions, can be found in Chapter 4, Section AVI in Appendix A and Appendix C.

The levelised cost of electricity indicator considers the full 'cradle to grave' life cycle as shown in Figure 6. The capital cost and fuel cost indicators consider 'gate to gate' and 'cradle to gate' system boundaries, respectively. A 'gate to gate' life cycle is considered for the capital cost indicator and considers only the capital cost required to construct the power plant. A 'cradle to gate' life cycle is considered for the fuel cost indicator and considers the costs required to produce shale gas (capital cost of well site and operation and maintenance costs) as well as cost to transport the gas to the power plant. All three economic indicators have a functional unit; the generation of 1 kWh of electricity in the power plant.

Table 5: LCC indicators used to assess the economic sustainability.

Impact category	Description
Levelised cost of electricity	The ratio of total cost inputs to total electricity generated by the power plant over its lifespan. Measured in pence/kWh.
Capital cost	The ratio of total capital cost of the power plant to the total amount of electricity generated by the plant over its lifespan. Measured in pence/kWh.
Fuel cost	The ratio of the total cost of fuel to the power plant to the total amount of electricity generated over the plants lifespan. Measured in pence/kWh.

4.5.3. Social sustainability assessment

The social sustainability assessment has been conducted based on life cycle thinking (Azapagic et al., 2011) . This has been carried out using the 14 indicators given in Table 6. These indicators have been selected following the findings of the literature review (Chapter 2). For further details on the social sustainability indicators and the methodology followed, see Chapter 5, Section AVII in Appendix A and Appendix D. A ‘cradle to grave’ life cycle is considered for three of the indicator (direct employment, worker injuries and direct community investment) while for others a ‘cradle to gate’ system boundary is considered. The indicators: local employment, noise, traffic land use conflict, media bias, regulation, gender equality and spending on local suppliers, consider the stages of site exploration and development to gas extraction. Public support and diversity of fuel supply consider the stages from gas extraction to power plant utilisation. Wastewater treatment considers only the gas extraction stage.

The indicators direct employment and worker injuries also have a functional unit and are calculated per kWh or electricity generated. The other 12 indicators do not have a functional unit.

Table 6: Social sustainability assessment indicators used to assess the social sustainability.

Impact category	**Description**
Public support	Net public support for an electricity option.
Worker injury	The ratio of total injuries (based on statistics) which could occur over the life cycle of a electricity option to the total amount of electricity generated by the power plant. Measured in injuries/kWh.
Direct employment	The ratio of the total number of full-time jobs created in each stage of an electricity options’ life cycle, to the total amount of electricity generated by the plant. The employment generated takes into consideration the duration of jobs as well as the total number of jobs created. The jobs created by operators are considered. Indirect and induced jobs created in the supply chain have not been considered, as well as jobs that would be created by the need to regulate or inspect operations. Measured in person-year/kWh.
Local employment	The percentage of jobs created in the shale gas electricity life cycle which could go to local residents.
Diversity of fuel supply	The security of energy supplies taking into consideration the amount of fuel produced indigenously and the amount imported from abroad. The countries from where fuel is imported from are also taken into consideration.
Noise	The amount of noise, measured in decibels (dB), generated by activities common in shale gas development. Equivalent continuous sound level is considered.

Table 6. (Continued)

Impact category	Description
Traffic increase	The percentage increase in traffic and road congestion expected as a result of bringing a shale gas well into operation.
Land use conflict	The overlapping of land which could potentially be drilled for shale gas with sites of cultural and scientific value and importance. Measured using a binary overlap approach. The impact of setback distances and buffer zones have not been considered as they would have added additional complexity to this analysis and could not be incorporated in the method used for the binary overlap. The aim of this indicator is to identify visually any potential conflicts in land use.
Wastewater treatment	The amount of wastewater generated by a shale gas well over its lifespan and the impact this could have on wastewater treatment facilities. This takes into consideration the treatment plant's processing capability.
Media bias	The presence of different shale gas development stakeholders on popular social media platforms. Measures how much online visibility and presence different stakeholders have online in social media and gives a measurement of the type of information most widely available to social media users.
Regulatory staff requirements	The identification on whether the UK has adequate staffing numbers for regulating a UK shale gas industry was determined by calculating the number of inspectors needed per shale gas well drilled. This was then compared with the number of inspectors currently employed for inspecting UK oil and gas wells.
Gender equality	The ratio of male to female workers in the UK oil and gas industry. This was used to identify whether gender equality is an area in which shale gas could help improve.
Spending on local suppliers	The percentage of capital spent by shale gas operators which could go to local suppliers and businesses.
Direct community investment	The amount of money given to local communities by the operators in the shale gas electricity life cycle. Shale gas operators will give £100,000 per well site and 1% of shale gas sales revenue, as defined in the community charter, to communities close to well sites. Gas distributors and power plant operators can invest and fund community projects and events in communities close to power plants or compressor stations. The total amount given to communities is calculated as a percentage of the total revenue of the operators. The aim is to measure the spread of wealth/revenue between operators and local communities.

4.5.4. Multi-criteria decision analysis

The results of the three sustainability assessments have been integrated using multi-criteria decision analysis (MCDA) to evaluate the overall sustainability of shale gas electricity and the other options. MCDA is a useful tool for problems with multiple and conflicting criteria, and when numerous options need to be considered and ranked on their performance (Azapagic and Perdan, 2005a; Azapagic and Perdan, 2005b). In this work, the simple multi-attribute rating technique (SMART) has been applied using the Web Hierarchal PREference (Web-HIPRE) software (Mustajoki and Hamalainen, 2000) . This method is based on a linear additive model and it involves scoring the sustainability criteria (indicators) in order of importance, followed by rating the options on a scale of zero to one and calculating the overall scores for the options, so that they can be ranked on their sustainability (Barford and Leleur, 2014; Edwards, 1977; Edwards and Barron, 1994). To do this, the options are first rated based on their performance in each indicator on a scale of zero to one, which is then converted into a score via value functions, which are mathematical functions used to convert preferences into numerical values (see Section AVIII in Appendix A for details). The option which has the worst performance is given a rating of zero while the best performing is given a rating of one. The remaining options are given intermediate ratings based on their performance in a particular sustainability indicator. When all the options have been rated, the criteria and indicators are weighted relative to their importance/preference. In the SMART method, the least important criterion is allocated a score of ten (Barford and Leleur, 2014) with more important criterion given higher scores, in order of their importance. In the base case, each criterion is given the same score (ten) and shifts in importance are analysed in a sensitivity analysis. The option which scores the highest is deemed the most sustainable option and vice versa. Further details on the SMART methodology can be found in Chapter 6 and appendices A and E.

4.5.5. Data quality assessment

To assess the validity of the LCA, LCC and social sustainability results and to identify data improvements for future work, a data quality assessment has been carried out. This is particularly important because of the lack of actual field data for shale gas exploration in the UK. The pedigree matrix method is used for these purposes and has been applied to the LCA, LCC and social sustainability assessment data. As indicated in Table 7, the pedigree matrix grades the quality of data on a number of criteria on a scale one to five (Althaus et al., 2007; Weidema et al., 2013). In this work, the data is graded for each characteristic using this scale and the scores added up to give the overall data quality score. These are then averaged to calculate the average data quality for each of the three sustainability aspects (environmental, economic and social). More details on the data quality assessment can be found in Chapter 6 and Appendix E.

4.6. Conclusions and recommendations

Following the sustainability assessment and ranking of the different electricity options, conclusions on whether or not shale gas resources are a sustainable option for UK electricity can be drawn, in addition to recommendations which can be used by regulators and shale gas operators on how to improve its sustainability. These can be found in Chapter 7.

Table 7: Pedigree matrix characteristic and grading criteria used for assessing data quality (Althaus et al., 2007; Weidema et al., 2013). This table lists the generic grading characteristics. For the specific grading characteristics, refer to Table E2 in Appendix E.

	Grade				
Characteristic	*1 (High)*	*2*	*3*	*4*	*5 (Low)*
Reliability	Verified based on field/lab measurements	Partially verified based on field/lab measurements	Partially verified based on estimates	Verified estimates	Non-verified
Completeness	Representative of all sites for adequate time period	Representative of most sites for adequate time period	Representative of some sites over an adequate time period	Representative of very few sites and over an adequate time period	Unknown representativeness
Temporal correlation	Data relatively new	Data a few years old	Data over ten years old	Data over 15 years old	Unknown age
Geographical correlation	Area of study	Large area including study are	Area similar to study area	Area with some similarities to study area	Completely different area
Further technological correlation	Data from operator	Data not from operator but for same technology	Data for similar technology	Data for different technology with similar processes	Laboratory scale data
Sample size	Large (>100)	Large-medium (>20)	Medium (>10)	Small (>3)	Unknown

References

Adgate, J. L., Goldstein, B. D. and McKenzie, L. M. **2014**. Potential public health hazards, exposures and health effects from unconventional natural gas development. *Environmental Science and Technology*, 48, 8307-8320.

Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Roland Hischier, Nemecek, T., Rebitzer, G., Spielmann, M. and Wernet, G. **2007**. *Overview and methodology: Data v2.0 (2007)*. *The ecoinvent Centre*. Zurich, CH. Retrieved from: http://www.ecoinvent.org/database/older-versions/ecoinvent-version-2/methodology-of-ecoinvent-2/methodology-of-ecoinvent-2.html.

Andrews, I. J. **2013**. *The Carboniferous Bowland Shale gas study: geology and resource estimation*. *British Geological Society (BGS)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/226874/BGS_DECC_BowlandShaleGasReport_MAIN_REPORT.pdf.

Armor, J. N. **2013**. Emerging importance of shale gas to both the energy & chemicals landscape. *Journal of Energy Chemistry*, 22, 21-26.

Austvik, O. G. **2016**. The Energy Union and security-of-gas supply. *Energy Policy*, 96, 372-382.

Azapagic, A. and Perdan, S. **2005a**. An integrated sustainability decision-support framework Part I: Problem structuring. *International Journal of sustainable Development and World Ecology*, 12, 98-111.

Azapagic, A. and Perdan, S. **2005b**. An integrated sustainability decision-support framework Part II: Problem analysis. *International Journal of Sustainable Development and World Ecology*, 12, 112-131.

Azapagic, A., Perdan, S., Krewitt, W., Muller-Stichnithe, H., Darton, R., Pehnt, M., Stichnothe, H., Espinoza-Orias, N., Fenner, R., Flores, A., Bows, A., Anderson, K., Chalabi, Z. and Fletcher, T. **2011**. *Sustainable development in practice: Case studies for engineers and scientists*, Chichester, UK: Wiley-Blackwell.

Bamberger, M. and Oswald, R. E. **2012**. Impacts of gas drilling on human and animal health. *New Solutions*, 22, 51-77.

Barford, M. B. and Leleur, S. **2014**. *Multi-criteria decision analysis for use in transport decision making*. *Technical University of Denmark*. Lyngby, DK. Retrieved from: http://orbit.dtu.dk/en/publications/multicriteria-decision-analysis-for-use-in-transport-decision-making(aa15f7cc-eb6b-4ca4-ab79-994453751544).html.

Baroness Kramer. **2014**. *Infrastructure Bill*, The Stationery Office (TSO), London, UK.

Becklumb, P., Chong, J. and Williamns, T. **2015**. *Shale gas in Canada: Environmental risks and regulation*. *Economic, Resources and International Affairs Division Parliament of Canada*. Ottowa, CA. Retrieved from: http://www.lop.parl.gc.ca/content/lop/ResearchPublications/2015-18-e.html#ftn18.

BEIS. **2017a**. *Digest of United Kingdom energy statistics 2017*. *Department for Business, Energy and Industrial Strategy (BEIS)*. London, UK. Retrieved from: https://www.gov.uk/government/statistics/digest-of-uk-energy-statistics-dukes-2017-main-report.

BEIS. **2017b**. *UK energy in brief 2017*. *Department for Business, Energy and Industrial Strategy (BEIS)*. London, UK. Retrieved from: https://www.gov.uk/government/statistics/uk-energy-in-brief-2017.

BP. **2014**. *BP statistical review of world energy June 2014*. *British Petroleum (BP)*. London, UK. Retrieved from: http://www.bp.com/content/dam/bp-country/de_de/PDFs/brochures/BP-statistical-review-of-world-energy-2014-full-report.pdf.

Brown, D. R., Lewis, C. and Weinberger, B. I. **2015**. Human exposure to unconventional natural gas development: A public health demonstration of periodic high exposure to chemical mixtures in ambient air. *Journal of Environmental Science and Health, Part A*, 50, 460-472.

Buckley, N. **2015**. Eastern European shale gas exploration on ice as boom turns to bust. *Financial Times (FT)*, 28 October 2015, Available from: https://next.ft.com/content/72a0fbd4-7cae-11e5-a1fe-567b37f80b64.

Canadian Electricity Association. **2006**. *Power generation in Canada: a guide*. *Canadian Electricity Association*. Ottowa, ON, CA. Retrieved from: http://www.electricity.ca/media/pdfs/EnvironmentallyPreferrablePower/2-powergenerationincanada.pdf.

Clark, C., Burnham, A., Harto, C. and Horner, R. **2013**. *Hydraulic fracturing and shale gas production: Technology, impacts, and regulations*. *Argonne National Laboratory*. Oak Ridge, TN, USA. Retrieved from: http://www.afdc.energy.gov/uploads/publication/anl_hydraulic_fracturing.pdf.

Clark, P. and Bounds, A. **2015**. Ministers freed to intervene in fast-track fracking drive. *Financial Time (FT)*, August 13, 2015, Available from: https://next.ft.com/content/a346b038-4114-11e5-b98b-87c7270955cf.

Conti, J. J., Holtberg, P. D., Beamon, J. A., Napolitano, S. A., Schaal, M. and Turnure., J. T. **2013**. *Annual energy outlook 2013 with projection to 2040*. *US Energy Information Administration (EIA)*. Washington DC. Retrieved from: http://www.eia.gov/forecasts/aeo/pdf/0383%282013%29.pdf.

Conti, J. J., Holtberg, P. D., Diefenderder, J. R., Napolitano, S. A., Schaal, M., Turnure, J. T. and Westfall, L. D. **2015**. *Annual energy outlook 2015 with projections to 2040*. *Energy Information Administration (EIA)*. Washington DC. Retrieved from: http://www.eia.gov/forecasts/aeo/pdf/0383%282015%29.pdf.

Cronin, K. **2013**. *Community engagement charter oil and gas from unconventional reservoirs*. *UK Onshore Oil and Gas (UKOOG)*. London, UK. Retrieved from:

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/256360/Publication_UKOOG_communityengagementcharterversion6.pdf.

Crooks, E. **2016**. Cheniere Energy's shipment turns US into gas exporter. *Financial Times (FT)*, Available from: https://next.ft.com/content/f1773832-b5ee-11e5-b147-e5e5bba42e51.

Cuadrilla Resources. **2015**. *Our Lancashire sites* [Online]. Available: http://www.cuadrillaresources.com/our-sites/lancashire-sites/ [Accessed June 2015].

DECC. **2010**. *2050 pathways analysis*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/42562/216-2050-pathways-analysis-report.pdf.

DECC. **2013a**. *Digest of United Kingdom energy statistics 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/279523/DUKES_2013_published_version.pdf.

DECC. **2013b**. *Electricity generation costs*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/publications/electricity-generation-costs-december-2013.

DECC. **2013c**. *Onshore oil and gas exploration in the UK: regulation and best practice*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/503067/Onshore_UK_oil_and_gas_exploration_England_Dec15.pdf.

DECC. **2013d**. *UK energy in brief 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224130/uk_energy_in_brief_2013.PDF.

DECC. **2014**. *UK energy in brief 2014*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/350941/UK_Energy_in_Brief_2014_revised.pdf.

DECC. **2016**. *UKCS oil and gas production projections*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/503852/OGA_production_projections_-_February_2016.pdf.

Demirbas, A. **2010**. *Methane gas hydrate*, London, UK: Springer.

Edwards, W. **1977**. How to use multiattribute utility measurement for social decisionmaking. *IEEE Transactions on Systems, Man and Cybernetics*, SMC-7, 326-339.

Edwards, W. and Barron, F. h. **1994**. SMARTS and SMARTER: Improved simple methods for multiattribute utility measurement. *Organizational behaviour and human decision processes*, 60.

EIA. **2013**. *U.S. energy-related carbon dioxide emissions, 2012*. October, 2013. *US Energy Information Administration (EIA)*. Washington DC. Retrieved from: http://www.eia.gov/environment/emissions/carbon/pdf/2012_co2analysis.pdf.

EIA. **2014**. *Countries* [Online]: US Energy Information Administration (EIA). Available: http://www.eia.gov/countries/ [Accessed December 2014].

Elliot, D. **2007**. *Nuclear or not? Does nuclear power have a place in a sustainable energy future?*, New York, USA: Palgrave Macmillan.

Frei, C., Whitney, R., Schiffer, H.-W., Rose, K., Rieser, D. A., Al-Qahtani, A. and Thomas, P. **2013**. *World energy scenarios: Composing energy futures to 2050*. *World Energy Council*. London, UK. Retrieved from: https://www.worldenergy.org/wp-content/uploads/2013/09/World-Energy-Scenarios_Composing-energy-futures-to-2050_Full-report.pdf.

Freyman, M. and Salmon, R. **2013**. *Hydraulic fracturing and water stress: Growing competitive pressures for water*. *Ceres*. Boston, MA, USA. Retrieved from: http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers.

Girit, S. **2016**. Turkey faces big losses as Russia sanctions bite. *BBC*, 2 January 2016, Available from: http://www.bbc.co.uk/news/world-europe-35209987.

Gosden, E. **2014**. Total to invest £30m in Britain's shale gas hunt. *The Telegraph*.

Gosden, E. **2017**. Cuadrilla starts drilling at Lancashire fracking site. *The Times*, 18 August 2017, Available from: https://www.thetimes.co.uk/article/cuadrilla-starts-drilling-at-lancashire-fracking-site-qn85dgtkf.

Heijungs, R., Guinée, J. B., Huppes, G., Lankreijer, R. M., Udo de Haes, H. A., Wegener Sleeswijk, A., Ansems, A. M. M., Eggels, P. G., Duin, R. v. and Goede, H. P. d. **1992**. *Environmental life cycle assessment of products: guide and backgrounds (Part 1)*. *Centre of Environmental Science (CML), Leiden University*. Leiden. Retrieved from: https://openaccess.leidenuniv.nl/handle/1887/8061.

HM Treasury. **2013**. *Autumn statement 2013*, The Crown, London, UK.

HM Treasury. **2014**. *Autumn statement 2014*, The Crown, London, UK.

House of Lords. **2008**. *The economics of renewable energy*. *House of Lords: Economic Affairs Committee*. London, UK. Retrieved from: https://www.publications.parliament.uk/pa/ld200708/ldselect/ldeconaf/195/195i.pdf.

Huda, S. **2014**. Feasibility of KSA's shale gas project. *Arab News*, February 21, 2014, Available from: http://www.arabnews.com/news/528631.

IEA. **2011**. *World energy outlook 2011: Are we entering a golden age of gas?* . *International Energy Agency (IEA)*. Paris, FR. Retrieved from: http://www.worldenergyoutlook.org/media/weowebsite/2011/weo2011_goldenageofgasreport.pdf.

IEA. **2015a**. *Energy and climate change*. *International Energy Agency (IEA)*. Paris, FR. Retrieved from: https://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf.

IEA. **2015b**. *Key world energy statistics*. *International Energy Agency (IEA)*. Paris, FR. Retrieved from: http://www.iea.org/publications/freepublications/publication/KeyWorld_Statistics_2015.pdf.

ISO. **2006a**. *EN ISO 14040: 2006 Environmental management - Life cycle assessment - Principles and framework*. International Organization for Standardization (ISO). Geneva, CH.

ISO. **2006b**. *EN ISO 14044:2006 Environmental management - Life Cycle assessment - Requirements and guidelines*. International Organization for Standardization (ISO). Geneva, CH.

Jackson, R. B., Vengosh, A., Carey, J. W., Davies, R. J., Darrah, T. H., O'Sullivan, F. and Petron, G. **2014**. The Environmental Costs and Benefits of Fracking. *Annual Review of Environment and Resources*, 39.

Koppelmann, B., Walker, A. and Woods., E. **2012**. *Shale gas extraction in the UK: A review of hydraulic fracturing*. *The Royal Academy of Engineering*. London, UK. Retrieved from: https://royalsociety.org/~/media/policy/projects/shale-gas-extraction/2012-06-28-shale-gas.pdf.

Kuuskraa, V. A., Stephens, S. H. and Moodhre, K. D. **2013**. *Technically recoverable shale oil and shale gas resources: An assessment of 137 shale formations in 41 countries outside the United States*. *U.S. Energy Information Administration (EIA)*. Washington DC. Retrieved from: https://www.eia.gov/analysis/studies/worldshalegas/.

Lewis, C., Speirs, J. and MacSweeney, R. **2014**. *Getting ready for UK shale gas: Supply chain and skills requirements and opportunities*. *United Kingdon Onshore Oil and Gas and Ernst and Young*. London, UK. Retrieved from: http://www.ey.com/Publication/vwLUAssets/Getting_ready_for_UK_shale_gas/$FILE/EY-Getting-ready-for-UK-shale-gas-April-2014.pdf.

Litten, S. **2011**. Shale Gas, Hydrofracking, and Managing Risk. *Hudson River Environmental Society* [Online]. Available:

http://www.hres.org/joomla/index.php?option=com_content&view=article&id=78:shale-gas-hydrofracking-and-managing-risk-&catid=54:opinion&Itemid=64 [Accessed: October 2015].

Lofthouse, J., Simmons, R. T. and Yonk, R. M. **2015**. *Reliability of renewable energy: Biomass*. *Institute of Political Economy, Utah State University*. Logan, UT, USA. Retrieved from: http://www.usu.edu/ipe/wp-content/uploads/2015/11/Reliability-Biomass-Condensed.pdf.

Loh, L. J., Bandara, G. C., Weber, G. L. and Remcho, V. T. **2015**. Detection of water contamination from hydraulic fracturing wastewater: a [small mu]PAD for bromide analysis in natural waters. *Analyst*, 140, 5501-5507.

Lucas, E. and Miller, A. C. **2014**. Putin's pipelines. *The Economist*, 3 April 2014, Available from: http://www.economist.com/blogs/graphicdetail/2014/04/daily-chart-1.

Mackay, D. J. C. and Stone., T. J. **2013**. *Potential greenhouse gas emissions associated with shale gas extraction and use*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/237330/MacKay_Stone_shale_study_report_09092013.pdf.

Mason, R. **2015**. UK to close all coal power plants in switch to gas and nuclear. *The Guardian*, 18 November 2015, Available from: http://www.theguardian.com/environment/2015/nov/18/energy-policy-shift-climate-change-amber-rudd-backburner.

McGlade, C., Bradshaw, M., Anandarajah, G., Watson, J. and Ekins., P. **2014**. *A bridge to a low-carbon future? Modelling the long-term global potential of natural gas - Research report*. November, 2014. *UK Energy Research Council (UKERC)*. London, UK. Retrieved from: http://www.ukerc.ac.uk/publications/gas-as-a-bridge.html.

MCOR. **2010**. *Cross section of typical horizontal well* [Online] University Park, PA, USA: Marcellus Centre of Outreach and Research (MCOR). Available: http://www.marcellus.psu.edu/resources/maps.php [Accessed November 2013].

Mokhatab, S. and Poe, W. A. **2012**. *Handbook of natural gas transmission and processing*, Second, Oxford, UK: Elsevier.

Moniz, E. J., Jacoby, H. d., Meggs, A. J. M., Armstrong, R. C., cohn, D. R., Connors, S. R., Deutch, J. M., Ejaz, Q. J., Hezir, J. S., Kaufman, G. M., Kenderdine, M. a., O'Sullivan, F., Paltsev, S., Parsons, J. E., Perez-Arriaga, I., Reilly, J. M., Seto, C., Webster, M. D., Yang, Y., McRae, G. S. and Ruppel, C. **2011**. *The future of natural gas: an interdisciplinary MIT study*. *Massachusetts Institute of Technology Energy Initiative (MITEI)*. Cambridge, MA, USA. Retrieved from: https://mitei.mit.edu/system/files/NaturalGas_Report.pdf.

Montgomery, C. **2013**. *Fracturing fluid components*, Tulsa, OK, USA: InTech.

Moore, V., Bereford, A., Gove, B., Underhill, R., Parnham, S., Crow, H., Cunningham, R., Huyton, H., Sutton, J., Melling, T., Billings, P. and Salter, M. **2014**. *Hydraulic fracturing for shale gas in the UK: Examining the evidence for potential environmental impacts*. *The Royal Society for the Protection of Birds (RSPB)*. London, UK. Retrieved from: https://www.rspb.org.uk/Images/shale_gas_report_evidence_tcm9-365779.pdf.

Mundada, A. S., Shah, K. K. and Pearce, J. M. **2016**. Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems. *Renewable and Sustainable Energy Reviews*, 57, 692 - 703.

Mustajoki, J. and Hamalainen, R. P. **2000**. Web-HIPRE: Global decision support by value tree and AHP analysis. *Information Systems and Operational Research (INFOR)*, 38, 208-220.

Oil & Gas 360. **2015**. China has reduced its shale drilling and completion costs by 23%. *Oil & Gas 360* [Online]. Available: http://www.oilandgas360.com/china-has-reduced-its-shale-drilling-completion-costs-by-23/ [Accessed: 5 May 2016].

Osborn, S. G., Vengosh, A., Warner, N. R. and Jackson, R. B. **2011**. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings of the National Academy of Sciences*, 108, 8172-8176.

POSTnotes. **2014**. *Intermittent electricity generation*. *Parliamentary Office of Science and Technology (POST)*. London, UK. Retrieved from: http://researchbriefings.files.parliament.uk/documents/POST-PN-464/POST-PN-464.pdf.

PwC. **2011**. *Shale Gas: A renaissance in US manufacturing*. *PricewaterhouseCoopers (PWC)*. Washington DC. Retrieved from: http://www.pwc.com/us/en/industrial-products/publications/shale-gas.html.

PwC. **2012**. *Shale gas: Reshaping the US chemicals Industry*. *PricewaterhouseCoopers (PWC)*. Washington DC. Retrieved from: https://www.pwc.com/us/en/industrial-products/publications/assets/pwc-shale-gas-chemicals-industry-potential.pdf.

Riley, A. **2013**. *Geopolitical and Economic Implications of the Shale Revolution*. *The City Law School, City University London*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224434/evidence-alan-riley.pdf.

Rosenbaum, L. July **2014**. List of bans worldwide. *Keeping tap water safe* [Online]Available from: http://keeptapwatersafe.org/global-bans-on-fracking/ [Accessed: 29 July 2014].

Santoyo-Castelazo, E. and Azapagic, A. **2014**. Sustainability assessment of energy systems: integrating environmental, economic and social aspects. *Journal of Cleaner Production*, 80, 119-138.

Sherr, J. **2016**. How Russia's relationship with Europe has evolved. *BBC News*, 5 January 2016, Available from: http://www.bbc.co.uk/news/world-europe-35154633.

Shiklomanov, I. A. and Rodda, J. C. **2003**. *World water resources at the beginning of the 21st century*, Cambridge, UK: Cambridge University Press.

Stamford, L. and Azapagic, A. **2012**. Life cycle sustainability assessment of electricity options for the UK. *International Journal of Energy Research*, 36, 1263-1290.

Stephenson, M. H. **2016**. Shale gas in North America and Europe. *Energy Science and Engineering*, 4, 4-13.

Stephenson, T., Valle, J. E. and Riera-Palou, X. **2011**. Modeling the Relative GHG Emissions of Conventional and Shale Gas Production. *Environmental Science and Technology*, 45, 10757-10764.

Taylor, C. and Lewis, D. **2013**. *Getting shale gas working*. *Institute of Directors (IoD)*. London, UK. Retrieved from: www.iod.com/~/media/.../IoD_Getting_shale_gas_working_MAIN_REPORT.pdf.

thinkstep. **1992-2016.** GaBi software-system and database for life cycle engineering *6.115 6.115* thinkstep AG: Stuttgart, DE.

Third Energy. **2016**. *Assets and operations: Onshore* [Online] East Knapton , UK: Third Energy. Available: https://www.third-energy.com/assets-operations [Accessed February 2017].

Tobin, J., King, R. F., Morehouse, D. F., Trapmann, W. A. and Mariner-Volpe, B. **1999**. *Natural gas 1998: Issues and trends*. *Energy Information Administration (EIA)*. Washington DC. Retrieved from: http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/natural_gas_1998_issues_trends/pdf/it98.pdf.

UK Parliament. **2008**. *Climate change act 2008*, The Stationery Office (TSO), London, UK.

Wang, Z. and Xue, Q. **2014**. *The market structure of shale gas drilling in the United States*. *Resources for the Future (RFF)*. Washington DC. Retrieved from: http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-DP-14-31.pdf.

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O. and Wernet, G. **2013**. *Overview and methodology: Data quality guideline for ecoinvent database version 3 (final)*. *The ecoinvent Centre*. Zurich, CH. Retrieved from: https://www.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf.

Williams, J., Field, L. and Lee, E. **2011**. *The impact of unconventional gas in Europe: A report to Ofgem*. *Poyry (for Ofgem)*. Warrington. Retrieved from: https://www.ofgem.gov.uk/ofgem-publications/38113/033publicreportunconventionalgasofgemlogov41.pdf.

Williams, S. **2015**. Chevron pulls out of Poland shale. *The Wall Street Journal*, 31 January 2015, Available from: http://www.wsj.com/articles/chevron-pulls-out-of-poland-shale-1422717458.

World Nuclear Association. **2016**. *Nuclear Power in the United Kingdom* [Online] London, UK: World Nuclear Association. Available: http://www.world-nuclear.org/information-library/country-profiles/countries-t-z/united-kingdom.aspx [Accessed June 2016].

Zoveidavianpoor, M. and Gharibi, A. **2016**. Characterization of agro-waste resources for potential use as proppant in hydraulic fracturing. *Journal of Natural Gas Science and Engineering*, 36, Part A, 679-691.

Chapter 2. Shale gas: A review of the economic, environmental and social sustainability

This paper was published in the journal *Energy Technology* in April 2016 with the following citation:

> *Cooper, J., Stamford, L. and Azapagic, A. (2016), Shale Gas: A Review of the Economic, Environmental, and Social Sustainability. Energy Technology, 4: 772-792.*
> *http://dx.doi:10.1002/ente.201500464*

This paper presents a literature review and synthesis of the environmental, economic and social literature written about the impacts of shale gas development. Tables and figures have been amended to fit into the structure of this thesis. The status of Germany in Table 8 has also been updated. The results presented in Chapter 3 (a published paper) of this thesis were included as part of the literature reviewed in Section 3 of this paper. To fit into the structure of this thesis, references to this paper have been removed and figures 9 and 10 have been amended for the removal of this reference. Also, Section 6 of this paper listed recommendations (for government and industry) drawn from the literature reviewed. These have been moved to Chapter 7 (thesis conclusions and recommendations) to fit into the structure of this thesis. The thesis author is the main author of the paper and is the one who read and collated the information for the review paper and wrote the original manuscript. The co-authors are the supervisors of this PhD project and contributed towards the paper by reviewing the original manuscript and requesting additional data and information not present in the original manuscript.

Shale gas: A review of the economic, environmental and social sustainability

Jasmin Cooper, Laurence Stamford and Adisa Azapagic

School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester, M13 9PL, UK

*Corresponding author, Email: adisa.azapagic@manchester.ac.uk

Abstract

The growth of the shale gas industry in the US has raised expectations that other countries could boost domestic gas production, leading to lower energy prices and improved energy security. However, the degree to which the US experience is transferable to other countries is uncertain. Furthermore, the sustainability implications of shale gas development remains largely unknown. In an attempt to find out if and how it can be exploited in a sustainable way, the economic, environmental and social aspects of shale gas extraction and development are reviewed. These include costs, energy security, employment, water and land pollution, greenhouse gas emissions, earthquakes and public perception. The literature suggests that it is possible to develop shale gas in a sustainable way, but its future will depend on the industry being able to address the environmental concerns, the political will to see the industry through to maturity and public support, with the latter most likely being the biggest determinant.

Key words: economic costs; energy security; life cycle assessment; social sustainability; shale gas

1. Introduction

Recent estimates of large shale gas reserves across the globe (Kuuskraa et al., 2013) have raised expectations for cheap energy and improved security of supply, particularly as the consumption of natural gas is expected to triple by 2035 (IEA, 2011; IEA, 2014a; IEA, 2014b). Estimations show that shale gas could add 7,201 trillion cubic feet (tcf) to global gas reserves; by comparison, conventional gas reserves are estimated at 6,606 tcf (BP, 2014; Kuuskraa et al., 2013). A critical factor in gas consumption is that 73.5% of gas is traded (68% by pipeline and the rest as liquefied natural gas (LNG)), which means that there is a high dependency on imports in many countries (BP, 2014). For example, countries such as Japan and South Korea import all their gas, whereas the UK relies on imports for 55% of its demand (BP, 2014; DECC, 2013b; IEA, 2014a). A high dependency on imports can lead to high energy prices. For instance, the 2012 gas prices in Japan and the UK were US$15.89 and US$8.97 per GJ, respectively (BP, 2014). By contrast, the price of natural gas in the US, which is almost self-sufficient in this fuel, was US$2.62 per GJ (BP, 2014). The latter is a direct consequence of the exploitation of shale gas in the US, which is still the only country to produce it commercially on a large scale, despite 47 other countries having reserves (Kuuskraa et al., 2013). As shown in Table 8, 31 of these are or were actively looking into exploiting their reserves and are at different stages of development. The remaining 16 are undecided on whether or not to develop shale gas, either because their (estimated) resource is small or because their conventional gas reserves are much larger (Russia).

However, shale gas is controversial, with many people being opposed to it because of various sustainability issues associated with its exploitation and utilisation (Sovacool, 2014). In many cases, the environmental legacy associated with it overshadows the economic benefits, including groundwater and drinking water contamination as well as earthquakes (Koppelmann et al., 2012). This is due to the combined use of horizontal drilling and hydraulic fracturing to extract it from rock deep in the ground, which requires the use of water and chemicals (see Figure 7). Social and economic concerns have also been raised, including noise, increased traffic and possible conflicts of interest associated with royalties from mineral rights. As a consequence, shale gas has been banned in some countries, notably, France and Bulgaria (see Table 8).

Table 8: Current state of shale gas development in countries that have considered its exploration[a] (EIA, 2014a; Huda, 2014; Kuuskraa et al., 2013).

Country	Estimated reserves (tcf)	Technically recoverable (tcf)[b]	Current status	Motivation
Algeria	3,419	707	Starting: plans announced but no drilling	To meet growing domestic needs and to fulfil long-term contractual export obligations to Europe. However, domestic production is in decline.
Argentina	3,244	802	Exploration	To reduce reliance on gas imports and mitigate recent interruptions to exports (to Chile and Uruguay).
Australia	2,046	437	Small scale	Large LNG exporter, with long-term contractual obligations. Potentially, there could be an increase in domestic consumption if there was a switch from coal to gas electricity owing to a carbon tax on coal (which has since been withdrawn).
Bolivia	154	36	Not currently active, but considering and discussing development	To meet more easily contractual obligations to export to Argentina and Brazil.
Brazil	1,279	245	Not currently active, focusing on pre-salt and offshore activities	To reduce dependence on imports, which is increasing (by 27% between 2011 and 2012).
Bulgaria	66	17	Banned	Heavily dependent on gas imports (93%) from Russia; also heavily reliant on coal for electricity, so any plans to reduce coal dependence could increase gas capacity and demand.
Canada	2,413	573	Small scale	The fifth largest exporter of natural gas and plans to export LNG, but conventional production is declining. There is currently a moratorium on hydraulic fracturing in the province of New Brunswick.
Chile	228	48	Not currently active, but considering	To reduce reliance on imports (currently 100% of gas is imported).
China	4,746	1,115	Small scale	To satisfy increasing demand from all sectors and phase out coal to improve air quality. Have been dependent on gas imports since 2007.
Colombia	308	55	Exploration	To increase domestic production, increase exports, meet domestic needs and alleviate growing demand from power sector (owing to hydroelectricity shortages).

Table 8: (Continued)

Country	Estimated reserves (tcf)	Technically recoverable (tcf)[b]	Current status	Motivation
Denmark	159	32	Initial stages of exploration	A net gas exporter and exports expected to increase as domestic demand is expected to decrease owing to the Government pledge to be fossil fuel independent by 2050.
Egypt	535	100	Exploration, one test well (Amoun NE-3) drilled	Disruptions to exports because of a decline in domestic production and large growth in domestic demand. This has resulted in gas being diverted from export to the local market.
France	727	137	Banned	A net gas importer, with growing demand from energy and industry sectors.
Germany	80	17	Banned	Dependent on gas imports, of which a significant fraction comes from Russia. Coal makes up a large portion of electricity mix, so gas capacity may increase in the phasing out of coal.
Hungary		19	Exploration since 2005	Net gas importer, mostly from Russia. Gas provides a large portion of primary energy demand and expect to increase as a result of new gas-fired power plants being built and planned.
India	584	96	Exploration; test drilling	A net gas importer with expensive LNG contracts as domestic production is declining. Gas is used largely in the electricity sector, but disruptions in supply meant they had to switch to coal in 2011.
Libya	942	122	Evaluating reserves: activity slow owing to political unrest	To increase gas capacity in the power sector to free up oil for export and to improve LNG trade, which is now sold on the spot market owing to failure to meet long-term contracts.
Mexico	2,223	545	Exploration	To reduce imports of gas (mostly from the US) in the face of increasing demand (mostly owing to power generation).
Morocco	95	20	Not currently active, but considering. Public not convinced but industry (Shell) interested.	Heavily reliant on gas imports as 80% of gas is imported.
Pakistan	586	105	Starting exploration; core sample analysis in the US	Highly dependent (49%) on gas for primary energy. Domestic production recently fallen; import dependence is expected to increase.

Table 8: (Continued)

Country	Estimated reserves (tcf)	Technically recoverable (tcf)[b]	Current status	Motivation
Paraguay	350	75	Not currently active, but considering	To exploit its large resources and export to neighboring countries (despite current lack of gas infrastructure and demand).
Poland	763	148	Exploration	Heavily dependent on gas imports (mostly from Russia) and coal for electricity generation.
Romania	233	51	Exploration; moratorium from 2012 to 2013	Reliant on Russian imports to meet gas needs, as domestic production has been on a decline since 1983.
Saudi Arabia	600	600	Exploration since 2013	To increase domestic use, to shift power generation to gas to free up oil for export. There are no plans to export gas.
South Africa	1,559	390	Exploration; moratorium from 2011 to 2012	Heavily dependent on imports (from Mozambique) and want to reduce their reliance on coal for electricity.
Spain	42	8	Starting exploration: permits issued but no drilling	No domestic conventional gas production and all gas consumed is met by imports. As a result of the financial crisis in 2008, there was a shift in the electricity mix to coal, with incentives to boost domestic coal mining. Plans to phase out coal could increase gas capacity.
Tunisia	114	23	Currently considering developing but no decision made as of yet.	Heavily dependent on imports and electricity predominately from gas (97%).
UK	134[c]	26	Exploration	A net importer of gas and gas capacity for electricity is increasing as coal is being phased out.
Ukraine	572	128	Exploration, test drilling from 2012	Net importer of gas (from Russia). Gas is also a main primary fuel so they want to diversify their supply to reduce dependence on Russia.
US	4,644	1,161	Commercial	To reduce reliance on imports and become energy self-sufficient. Started exporting LNG in 2015.
Venezuela	815	167	Beginning exploration	To decrease imports and meet growing demand from industry. Roughly 16% of electricity is generated from oil, so increasing gas capacity will increase the amount of oil available for export.

[a] The table lists only those countries that have considered development of shale gas. The remaining 16 which have reserves but are undecided are not included.
[b] The volume of gas that can be extracted with current knowledge and technology. 1 trillion (10^{12}) cubic feet= 28 billion (10^9) cubic meters.
[c] The number is the estimation made by the EIA; the British Geological Survey (BGS) estimate the UK to have 1300 tcf in reserves (Andrews, 2013).

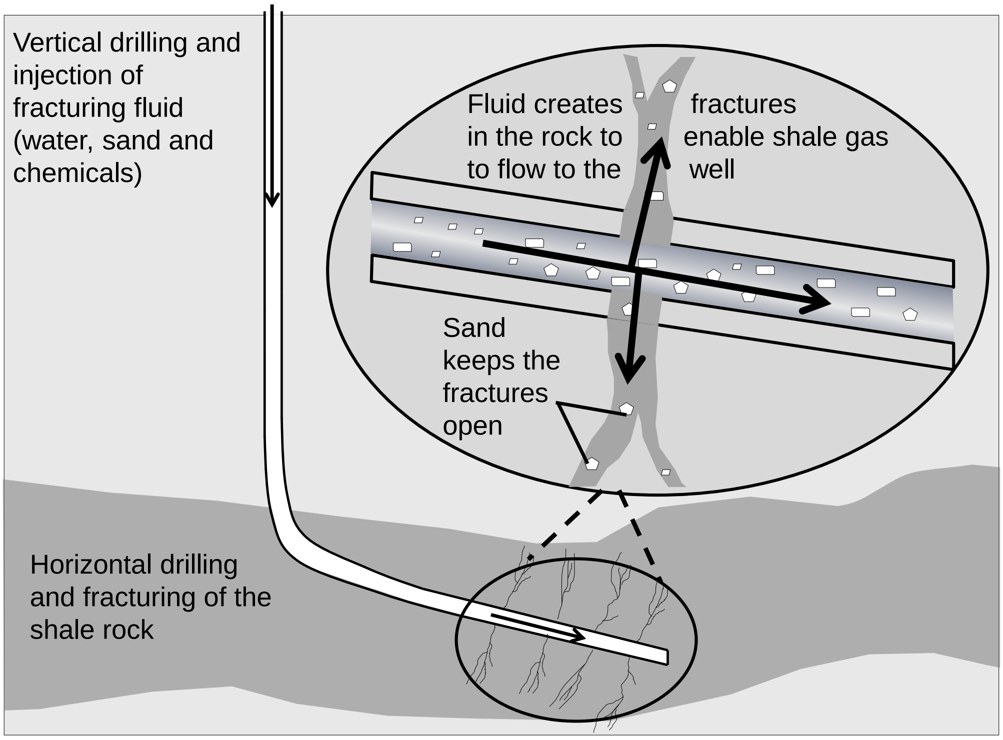


Figure 7: Typical profile of a shale gas well. The well consists of a vertical and horizontal section. The latter is hydraulically fractured with a mixture of water, sand and chemicals to release the gas from the shale.

Much has been written and discussed about different sustainability issues associated with shale gas exploitation. However, most literature and discussions focus on one or two aspects at a time, resulting in a lack of an overall picture as to how shale gas affects different issues, both positively and negatively. Therefore, this chapter sets out to provide a comprehensive overview of the economic, environmental and social sustainability of shale gas, with the aim of synthesising the findings in the literature.

2. Economic aspects

As the US is the only country to produce shale gas on a large commercial scale, this section first examines various economic aspects associated with shale gas here before looking at other regions.

2.1. The US experience

2.1.1. Direct impacts

In the US, domestic natural gas production has grown rapidly (Figure 8), from 17.8 tcf in 1990 to 24 tcf in 2013, and is predicted to reach 33.1 tcf by 2040 (Conti et al., 2013). Since 1990, some 43 tcf of shale gas has been produced and in 2013 over 35% of natural gas produced came from shale. The reserves are located in the lower 48 states, with production primarily in six main shale plays: Barnett, Eagle Ford, Fayetteville, Haynesville, Marcellus and Woodford (Conti et al., 2013; EIA, 2011). The large scale and rapid growth in production have created significant employment. As shown in Table 9, total direct, indirect and induced jobs in 2010, created because of the development of shale gas, was over 600,000; this is predicted to exceed 800,000 in 2015 and 1.6 million by 2035 (Fullenbaum et al., 2011). The sector also contributes significantly to the gross domestic product (GDP) and tax revenue, in 2010 estimated at US$76.9 million and US$18.6 million, respectively (Table 9).

The large-scale production of shale gas has also led to a sharp drop in gas prices (Figure 9); since 2008 the wellhead price (wholesale minus transport costs) decreased by 54% and, on average, residential, commercial and industrial gas prices dropped by 20% (EIA, 2014b). The (break-even) cost for wells (Table 10) has also decreased, making them more profitable. For example, in the Haynesville shale play, the (break-even) cost of new wells has fallen by over 40% since 2013 and is 18% lower than the Henry Hub spot gas price (Malik, 2015).

Prior to the ‘shale boom’, the US was expected to become a net importer of gas and constructed 11 LNG import terminals (CNLG, 2014). However, these are now being converted for export and, as of April 2013, 32 applications had been made to export LNG, with approved exportation volumes totalling 9.3 billion cubic feet per day, which is more than double the UK’s daily domestic production of natural gas (Arora and Cai, 2014; Office of Fossil Energy, 2013). Despite this, it is currently unclear what impact LNG exports will have on the domestic and international markets, but it is expected that US LNG will be important in meeting energy demands in Asia, which could lead to a rise in domestic gas prices as a result of growing demand (IEA, 2011).

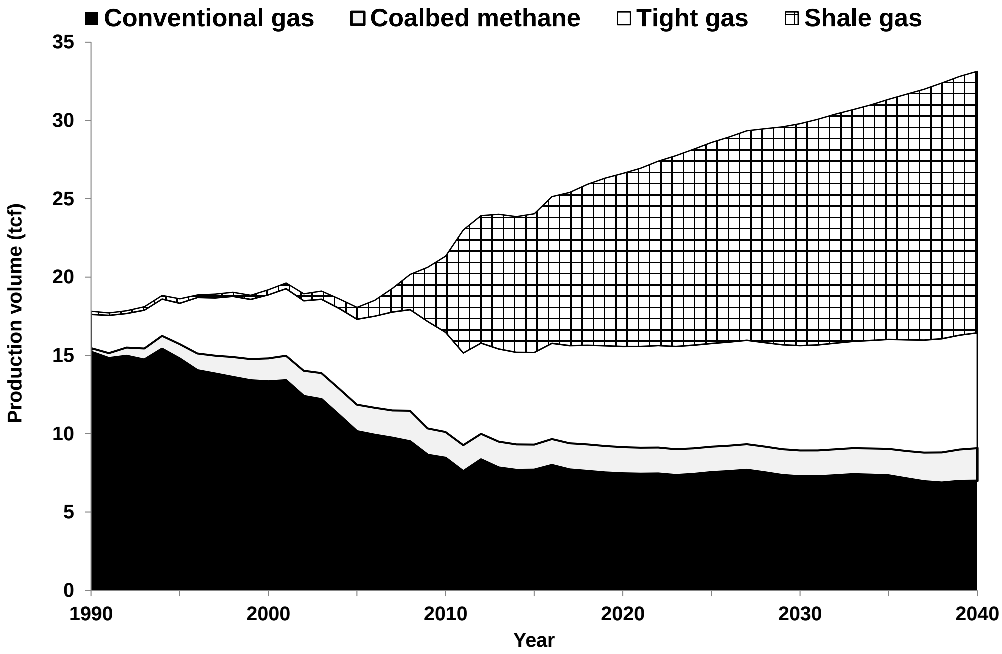


Figure 8: Historical and predicted future shale gas production in the US from 1990 to 2040 (Conti et al., 2013).

Table 9: Contribution of shale gas to the US economy in 2010(Fullenbaum et al., 2011).

	Direct	Indirect	Inducted	Total
Employment (no. of jobs)	148,143	193,710	259,494	601,348
GDP (million US$)	29,182	22,283	25,283	76,880
Tax revenue (million US$)	9,621[a]	8,825[b]	161[c]	18,607

[a] Federal tax revenue
[b] State and local tax revenue
[c] Federal royalties

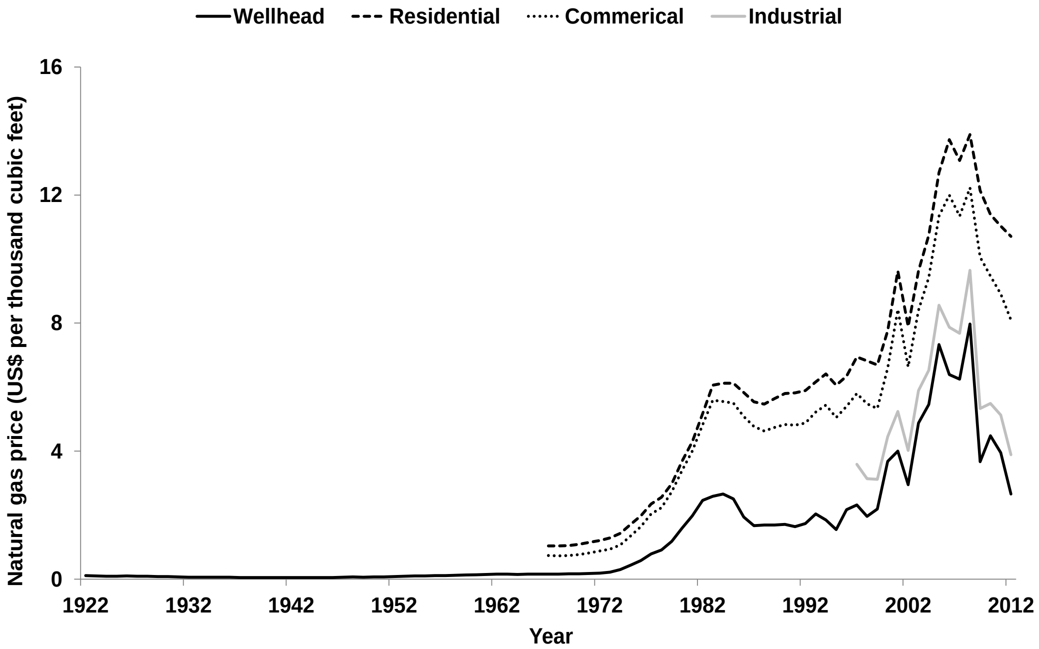


Figure 9: Changes in gas prices in the US from 1922 to 2012(EIA, 2014b).

2.1.2. Indirect impacts

The sharp drop in gas prices has led to its price decoupling from that of US oil and international gas (Webber, 2012). This is significant because elsewhere gas prices are set relative to oil and changes in the price of oil are often mirrored in gas prices. The US has bucked this trend: between 2009 to 2012, oil prices rose while gas prices fell (EIA, 2015).

As a result of having lower gas prices, the US is an attractive location to industry, in particular, chemicals and manufacturing. This can be seen in the recent investments made by large chemical companies, such as DOW Chemical and Sasol, to build new production sites in the US. DOW is investing US$4 billion in building new facilities in Texas and Sasol US$8.1 billion in Louisiana (Gilbert, 2012; Lauletta, 2014). Investments and projects such as these were made possible by the fact that gas prices are three to six times lower there than in other developed countries; thus, it is expected that the production of commodities will shift increasingly to the US (BP, 2014). This has the added benefit of cutting transportation costs for the world's largest consumer of commodities. The boost to industry is estimated to be worth billions, including US$72 billion in investment by 2020 (ACC, 2011). In addition to industrial growth, lower fuel costs will create savings in production, estimated at US$11.60 billion by 2025 (PwC, 2011; PwC, 2012).

The reinvigoration of industry is predicted to create one million jobs by 2025, which, when combined with employment generated from shale gas development itself (and its supply chain), could total more than two million jobs (PwC, 2011; PwC, 2012). Overall, this will lead to gains in GDP as total employment rises. Furthermore, because more commodities will be produced domestically, goods and services will likely be cheaper and spending will increase, again boosting GDP.

However, the recent slump in oil prices has put a question mark over the future of shale gas (and oil) production in the US. Wells that produce ‘wet gas’ (containing heavier hydrocarbons) are more profitable than those that produce ‘dry gas’ (mostly methane), as the liquids produced, such as ethane and propane, are more valuable than methane (FT, 2016). The price of the liquids is set relative to oil, so a drop in oil prices will cause a drop in the price of the hydrocarbon liquids; therefore, decreasing the profitability of these wells. Despite this, the USA shale gas industry is showing signs of resilience against the low oil prices because the rate of new well drilling has not been hit as badly as expected (Oil prices, 2015). This is believed to be because of technological advancements, such as drilling multiple and longer horizontal wells from a single vertical well and lower cost of materials (steel and cement).

2.2. Other regions

Outside the US, shale gas activity is much smaller in scale and lagging behind in development (Table 10), so that economic impacts in other countries can only be estimated. Large oil and gas companies have invested heavily in regions seen as promising, but only a few of these have analysed the economic significance of shale gas (Table 10). When comparing the estimated production cost to the US cost, it can be seen that, in comparison, shale gas is much more expensive to produce in other countries because of the lag in development.

As mentioned previously, the main motivation for developing shale gas in most regions is to increase energy security. Asia and Europe are the biggest importers of gas, with the Asian market having the highest gas prices (BP, 2014). Therefore, diversification of the gas mix is important for achieving a sustainable gas supply. However, another motivation is to sustain or grow industrial activity in general or in the case of net exporters, such as Canada, Australia and Algeria, to fulfil long-term export contracts, despite declining conventional reserves (Table 8).

The low gas prices in the US pose risks to some countries, such as the UK and Germany, because of companies importing feedstock from the US instead or relocating there. An example of this is INEOS, the largest chemical company in the UK, which is importing US shale gas ethane for its Grangemouth refinery because it is 75% cheaper than UK North Sea ethane (Gribben, 2014). However, if the UK were to develop shale gas, domestic ethane production could increase, resulting in ethane being cheaper than US imports, which is the main reason for INEOS’s decision to buy a £640 million share in UK shale gas licenses (Moylan, 2014). Therefore, it can be seen that, in addition to energy security, shale gas can also be important to industrial countries if they are to retain and grow their manufacturing capacity and capability.

To encourage investment into shale gas, some countries have introduced tax incentives. In the UK, the Government is currently offering a reduced tax rate for operators to encourage investment, as well as a shale gas fund and community charter (BIS, 2013; Cronin, 2013). The then Chancellor of the Exchequer, George Osborne, announced in the 2014 Autumn Statement a "*new long term investment fund from tax revenues from shale ... to capture the economic benefits … for future generations*" (HM Treasury, 2014). More recently, to speed up the planning process for shale gas development the Government has ordered local authorities to make decisions on planning applications within 16 weeks, at most, or otherwise the planning process will be taken out of their hands and centralised (Clark and Bounds, 2015). Other countries have reformed their energy market to increase foreign investment. For instance, in Mexico reforms mean private companies can now bid for oil and gas exploration licenses ('Ronda Uno'), ending the monopoly of state-owned PEMEX (Fowler, 2014).

Despite these reforms, many countries are facing obstacles in their development of shale gas. Barriers include gaining public support (see Section 4) as well as various political and technical issues. Countries in which the government controls the gas market, such as China, face the problem of uncompetitive market conditions because of a monopoly by national corporations or government-set gas prices being too low (Yunna et al., 2015). Technical barriers, on the other hand, stem from two issues: i) many countries lack the infrastructure, skills and expertise of the US; and ii) each shale gas well is unique and can present specific problems. This makes shale gas development capital intensive because much research and development (R&D) and exploratory work is needed for test wells and drilling. Furthermore, each well site will require different equipment (for drilling, hydraulic fracturing, gas treatment and waste management) and in many countries the construction of new infrastructure will be required to develop shale gas successfully. Consequently, the capital required is too high for many private companies (Bolton and Foxon, 2014; Tian et al., 2014; Yunna and Yisheng, 2014).

Table 10: Estimates of costs, investment and revenue for developing shale gas in other countries in comparison to the US.

Country	Estimated economic impacts[a]
Australia	Estimated that production costs are US$4.76-7.14 per GJ; by comparison the wholesale gas price is US$3.17 per GJ (Cook et al., 2013).
Canada	Estimated that in New Brunswick shale gas would require US$1,606 million in investment to generate US$1,184 million in GDP and 5,078 jobs per year between 2015 and 2020 (Jupia Consultants Inc., 2014); in Quebec US$5.9-17.7 billion is required in investment to generate US$27.8-83.3 billion in GDP and 293,000 to 880,000 jobs (Mersich, 2013).
China[b]	Some US$1.16 billion has already been spent on surveying and exploration (Chou, 2013).
Germany	Investment costs are estimated at US$7.5-28.4 billion, which would generate 114,782 to 431,700 jobs (direct, indirect and induced); the average production cost is estimated to be US$9.35 per GJ, which is higher than the cost of Russian gas imports (US$8.77 per GJ) (Bonetti, 2014).
Poland	Predicted that US$7.1 billion would be required in investment, generating US$6.2 billion in revenue and 15,000 direct and 204,000 indirect jobs (Cylwik et al., 2012).
UK	Estimated that some US$50 billion in investment is required, creating 32,000 to 74,000 jobs (AMEC, 2013; Lewis et al., 2014; Taylor and Lewis, 2013).
US	Cost (break-even) of producing shale gas ranges from US$2.37-6.47 per GJ (Berman and Pittinger, 2011; BNEF, 2013; Malik, 2015; Moniz et al., 2011; Weijermars, 2013).

[a] The original values reported for different countries converted to US$ (2015) by using the inflation rate (consumer price index (CPI)) for each country and exchange rates as follows: AUS$1=US$0.73, CPI (2013-2015): 8.71%; CAD$1=US$0.72, CPI (2013/14-2015):3.3% and 1.36%; €1=US$1.10, CPI(2014-2015):1.59%; PLN1=US$0.26, CPI(2012-2015):1.21%; £1=US$1.49, CPI(2013-2015):1.61% US values updated using the CPI (2011-2015) of 8.6%.
[b] The original value reported in US$. The inflation rate for China was not available so the US inflation rate, CPI (2013-2015): 3.63%, was used instead.

In addition, poor test results have been highlighted in the literature: test wells have been found to be less productive than expected and this has had major repercussions for several countries. For instance, major oil and gas companies, such as Exxon Mobil and Chevron, have pulled out of projects in Poland and Romania, significantly slowing down shale gas development there. In China, the Government had to cut its cumulative production target from 3,530 bcf by 2030 to 1,060 bcf (Cheng, 2014; Chou, 2013). This emphasises the fact that, as indicated in Table 10, development of shale gas may still be uneconomical for many countries outside the US.

3. Environmental aspects

Shale gas extraction is a relatively new process and, as a result, the earliest studies of its environmental impacts date from 2009/2010. Despite this, a large number of studies have been conducted, focusing mostly on the direct (local) impacts of hydraulic fracturing. There are also several life cycle assessment (LCA) studies, but most of them considered only greenhouse gas (GHG) emissions and climate change. As far as the author is aware, only one LCA study (besides the LCA conducted as part of this thesis; see Chapter 3) estimates a full range of impacts normally considered in LCA; the paper by the supervisors of this project (Stamford and Azapagic, 2014). This is based on UK conditions and provides life cycle impacts of electricity produced from shale gas in comparison to other electricity technologies. This and other studies are reviewed in the following sections, considering in turn impacts on the three environmental media: air, water and land.

Note that, inevitably, some of the environmental impacts also straddle social and economic aspects of sustainability, such as climate change and earthquakes, but for the purposes of this review, they are considered in this section with cross references to the other aspects of sustainability, as relevant.

3.1. Air emissions and impacts

Impacts considered in this section are those associated with air emissions. As mentioned above, GHG emissions have been studied most often in the literature, so this section starts by considering these first. This is followed by other gaseous emissions and their impact, including acidification, ozone layer depletion and photochemical smog.

3.1.1. GHG and climate change

The extent to which shale gas contributes to climate change is currently unclear. However, it is often suggested that using shale gas to replace coal for electricity generation will decrease GHG emissions. In the US, electricity generation from coal decreased from 2,016 TWh in 2007 to 1,514 TWh in 2012 (EIA, 2013). During this period, generation from natural gas (including shale gas) grew from 897-1,226 TWh and CO_2 emissions from the electricity sector fell from 2,426-2,029 Mt. Therefore, it could be argued that the widespread deployment of shale gas has helped to reduce GHG emissions in the US. However, the boom in shale gas has depressed coal prices, which has likely contributed to the increase in coal-fired electricity production in Europe (Broderick and Anderson, 2012). In the UK, for instance, the share of domestic electricity generation from coal increased from 29.5% in 2011 to 39.4% in 2012, the highest since the mid-1990s (DECC, 2013a).

Nevertheless, there is a general agreement in the literature that electricity from shale gas has lower life cycle GHG emissions and related climate change impacts, estimated as the global warming potential (GWP), than electricity from coal. The GWP of shale gas electricity reported in the literature ranges from 411-1,115 g $CO_{2\text{-Eq}}$./kWh, with an overall average across the studies of 506 g $CO_{2\text{-Eq}}$./kWh, as indicated in Figure 10. By comparison, the impact from coal electricity varies from 837-1,130 g $CO_{2\text{-Eq}}$./kWh (Mackay and Stone., 2013). The wide variation in the GWP of shale gas electricity is due to different technologies assumed for electricity generation (combined or single cycle gas turbine) and related differences in the efficiency, as well as the assumptions for fugitive methane emissions and the time horizon over which the GWP is estimated. For example, considering shorter time horizons (20 years instead of the more common 100 years) can lead to a higher GWP of shale gas electricity than of coal (Howarth et al., 2011), as the potency of methane to cause climate change is much higher in the short term (Stoker et al., 2013).

Regardless of the time horizon, methane emissions can significantly affect the GWP of shale gas. Sources of methane include fugitive emissions from equipment, pipelines and flowback water, as well as gas vented or flared during drilling and well completion (Brandt et al., 2014; Caulton et al., 2014; Ekstrom, 2014; Howarth et al., 2011; Jeong et al., 2014; Karion et al., 2013). Some studies have suggested that methane emissions of up to 12% of total gas production could negate any benefits of switching from coal to shale gas (Howarth et al., 2011; Karion et al., 2013; Stanek and Bialecki, 2014; Wigley, 2011). Other studies which considered energy transition scenarios with high methane emissions also concluded that the GWP of shale gas is similar to that of coal (Busch and Gimon, 2014; Levi, 2013; McGlade et al., 2014). However, these studies were largely based on estimates, whereas the results of a field study measuring methane emissions at well sites found them to be lower (Allen et al., 2013).

Various mitigation strategies can be employed to minimise methane emissions, including ‘green’ well completion (in which gas is separated from wastewater and utilised rather than vented or flared), reducing the amount of gas flared and vented during the production process and using infrared cameras to locate and minimise fugitive emissions (BP, 2012). In such cases, emissions are low enough for the GWP of shale gas to be comparable to those of conventional gas and LNG, making fuel-switching away from coal effective (Figure 11). However, even with very low methane emissions, the GWP of electricity from shale gas is several orders of magnitude higher than that of nuclear power and renewable power.

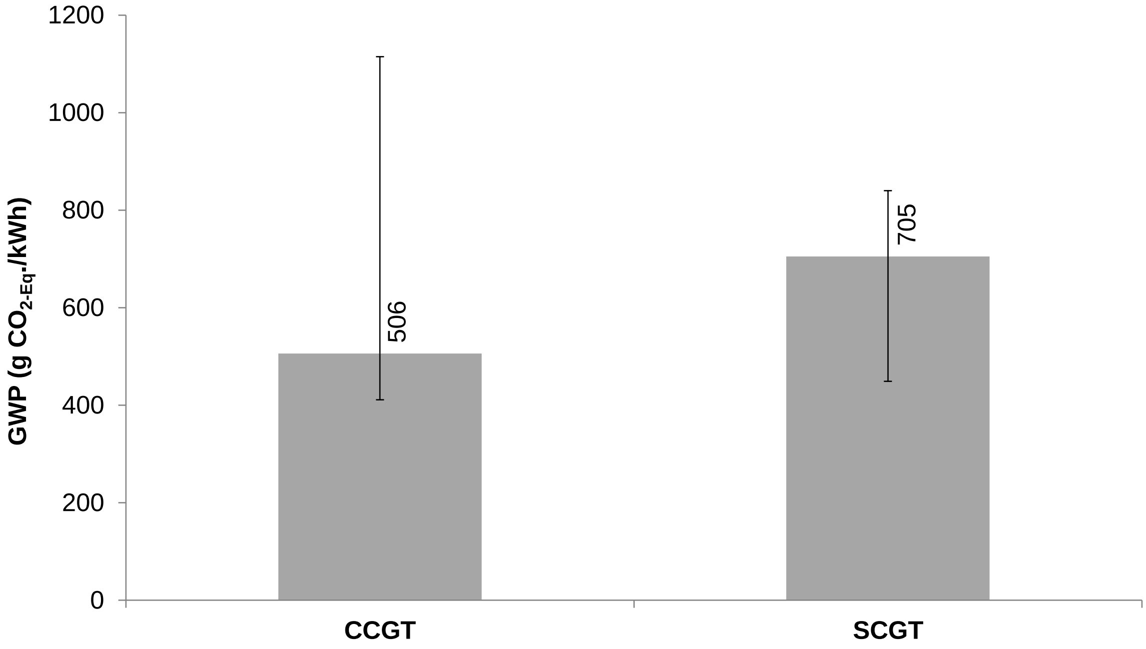


Figure 10: The global warming potential (GWP) of shale gas used for electricity generation. Combined cycle gas turbine (CCGT)(Broderick et al., 2011; Burnham et al., 2012; Clark et al., 2011; Dale et al., 2013; Forster and Perks, 2012; Hultman et al., 2011; Jiang et al., 2011; Laurenzi and Jersey, 2013; Mackay and Stone., 2013; Stamford and Azapagic, 2014; Skone et al., 2011; Stephenson et al., 2011; Weber and Clavin, 2012); single cycle gas turbine (SCGT) (Burnham et al., 2012; Clark et al., 2011; Hultman et al., 2011; Skone et al., 2011; Stephenson et al., 2011; Weber and Clavin, 2012). Data labels refer to the central GWP values and the error bars to the minimum and maximum values reported in the literature.

One other issue that is important, but has so far been largely neglected in the estimates of the GWP of shale gas is land-use change (LUC), related to the removal of vegetation to construct well pads, access roads and pipelines. To date, only one study has considered GHG emissions from LUC, finding that the GWP of shale gas can increase by up to ten times, depending on the type of soil (Bond et al., 2014). For example, developing shale gas on grassland would emit 1.21 g $CO_{2\text{-}Eq.}$/MJ of gas, whereas development on peat soils would lead to 13.41 g $CO_{2\text{-}Eq.}$/MJ (central case). This is because soils act as a carbon sink and if disturbed, through land clearance or other activities, releases carbon into the atmosphere as carbon dioxide and methane. As peat tends to store more carbon than other soil types, it also releases higher amounts than other soils. By comparison, total life cycle emissions excluding LUC are estimated at 1.66-2.89 g $CO_{2\text{-}Eq.}$/MJ (Bond et al., 2014).

3.1.2. Other air emissions and impacts

Various air pollutants are emitted during the extraction of shale gas, including volatile organic compounds (VOCs), nitrogen oxides (NO_x), alkanes, alkenes and silica particles (Armendariz, 2009; Colborn et al., 2014; Lyon and Chu, 2011; Mulloy, 2014; Myers and Poole, 2014; Olaguer, 2012; OSHA, 2014; Zavala-Araiza et al., 2014). The equipment used onsite is the main source of these emissions, in particular, compressors, condensate tanks and gas pipelines (Armendariz, 2009; Ekstrom, 2014; Sommariva et al., 2014).

The release of hydrogen sulphide (H_2S) during extraction is an important concern that has not been well studied. H_2S is a major hazard because it is poisonous to humans and is corrosive; the latter also means that it could corrode equipment and pipelines, releasing further H_2S and other chemicals into the environment. Incidents have been recorded in which the delayed release of H_2S has occurred following fracturing activity (Pirzadeh et al., 2014), but what causes this is unknown. However, it is hypothesised that chemicals used in fracturing fluids may be reacting with H_2S and microorganisms in the rock formation, leading to the release of H_2S (Pirzadeh et al., 2014; Cluff et al., 2014).

Measuring air emissions is a difficult task as variations in weather conditions (temperature, wind speed and direction, humidity, etc.) affect the measurements, as do nearby external sources of emissions, such as traffic and farming activities. A further issue is that most of the activities, such as well pad preparation, drilling and hydraulic fracturing, are episodic. This means that to establish whether these activities are affecting air quality, comparisons to baseline data need to be made, but these are typically not available. Inventory data are available for the US with estimates of pollutants emitted from shale gas, but field measurements have found the actual emissions to be significantly higher or lower than these estimates (Allen et al., 2013; Macey et al., 2014; Sullivan, 2014). However, most field studies cover short time periods (e.g., one day) and use low frequency monitoring, so that they are not fully representative (Anirban et al., 2014; Teasdale et al., 2014).

Emissions from shale gas extraction can be mitigated through the use of best available technology (BAT) and best practice. These include the use of ‘green’ well completion, not allowing gas to be vented or flared and detecting and fixing leaks in equipment and pipelines (Koppelmann et al., 2012; Mackay and Stone., 2013). Similar improvements in technology and regulation in the oil and gas sector have led to significant reductions in emissions compared with those in the 1980s/1990s (Field et al., 2014; Petron et al., 2012). Therefore, it is imperative to encourage or enforce the adoption of BAT and best practice in the shale gas sector.

Various other air pollutants are emitted in the rest of the life cycle of shale gas, causing air related impacts, such as acidification, ozone layer depletion and photochemical smog. Note that, strictly speaking, acidification is a water and land related impact, but because it is caused by air emissions of NO_x, SO_x, H_2S and NH_3, for the purposes of this review, it is considered in this section.

As mentioned earlier, only one LCA study has considered environmental impacts other than the GWP. The results are summarised in Figure 11 for the ten impacts considered in addition to the GWP (the results for the latter can also be found in Figure 10). As can be seen in Figure 11, the values for the impacts range widely. For example, the acidification potential (AP) is 7.5 times higher than conventional gas (Stamford and Azapagic, 2014). However, in the best case, shale gas has an AP comparable to conventional gas and lower than solar photovoltaic (PV). In the worst case, it is four times higher than coal.

The onsite combustion of diesel used for drilling and other equipment is the main contributor to the AP, as well as the removal of H_2S from raw gas (sweetening). Therefore, if the extracted gas is low in H_2S and the onsite equipment is powered from the electricity grid, this impact would be greatly reduced (Stamford and Azapagic, 2014). However, nuclear power and wind would have a lower AP (Figure 11).

In addition to acid gases, activities in the life cycle emit ozone-depleting substances, largely because of leakages of halon 1211 associated with pipeline transport (halons are used as fire retardants and coolants in various processes related to gas pipeline use and maintenance). However, these emissions are comparable to those from conventional gas, which in general has high ozone layer depletion potential (ODP) in comparison with the other options (Figure 11). For example, nuclear power and offshore wind have an ODP around 25 times lower than natural gas, including shale gas (Stamford and Azapagic, 2014). In the worst case, the ODP of shale gas is 85 times higher than wind (Stamford and Azapagic, 2014). Also, as indicated in Figure 11, the central ODP value is comparable to solar PV.

A further air related impact, photochemical oxidants creation potential (POCP), also known as photochemical smog, is due to leakage of VOCs during the sweetening process and emissions from onsite equipment. In the worst case, shale gas is 98 times worse than conventional gas and 18 times worse than coal (Figure 11). This is due to the venting of gas during well drilling and completion, assuming that all gas is vented. Therefore, gas venting regulations (such as the requirement for ‘green’ completions) are critical to reduce this impact (as well as the GWP). In comparison with other electricity technologies, shale gas has a much higher POCP: three times greater than solar PV, 26 times higher than offshore wind and 45 times higher than nuclear power (Figure 11). In the best case, shale gas is preferable to coal but wind and nuclear power are much lower.

3.2. Water use and impacts

Of all environmental issues, water related impacts associated with shale gas are the most widely studied and discussed, not only in the literature but also in the media; this issue is also one of the main objections by the public to shale gas, as discussed below. The section starts with an overview of water use and its potential contamination during shale gas extraction, followed by life cycle impacts associated with the discharge of various pollutants into water bodies along the supply chain.

3.2.1. Water use

One of the main arguments of those opposed to shale gas is that the high water requirements will increase stress on water supplies, particularly in water-scarce areas. However, in comparison with some other fuels, the water footprint of shale gas is lower (see Table 11) (Clark et al., 2013; Laurenzi and Jersey, 2013; Mekonnen et al., 2015; Scanlon et al., 2014). Similarly, when the water consumption per net energy recovered is considered, shale gas outperforms other fuels as shown in Table 11 (Goodwin et al., 2014).

Nevertheless, in absolute terms, the quantity of water required for hydraulic fracturing is large (up to 25,000 m^3), constituting 86% of direct water required for shale gas extraction and 56% of the overall consumption in the shale gas life cycle (Freyman and Salmon, 2013; Jiang et al., 2014). Undoubtedly, an increase in the scale of production will increase water consumption in a watershed. However, it is unclear how much of this can be attributed to shale gas alone since other activities, such as power plants and farmland, need to be taken into consideration when assessing water levels in a watershed (Pacsi et al., 2014; Scanlon et al., 2014).

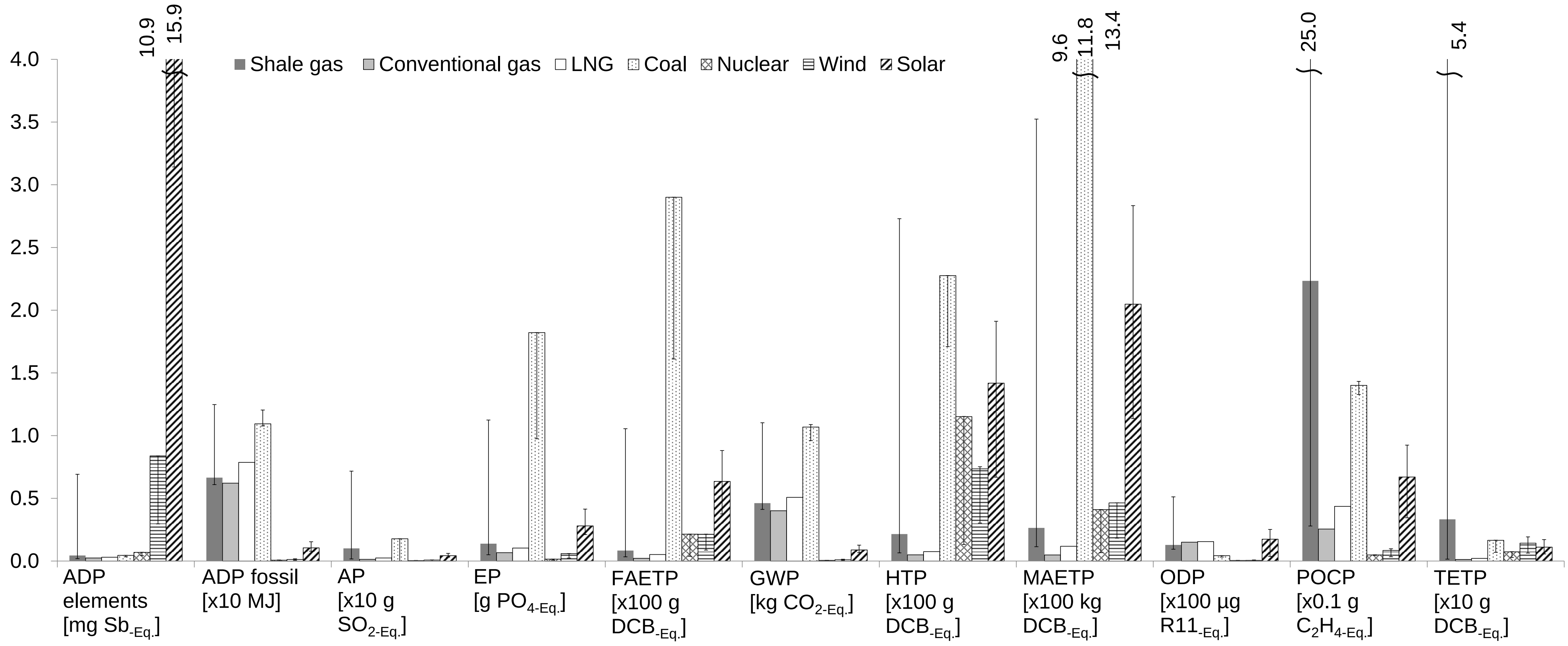


Figure 11: Life cycle environmental impacts of electricity from UK shale gas in comparison to other electricity options (Stamford and Azapagic, 2014). All impacts are expressed per kWh of electricity generated. LNG is imported from Qatar.

[ADP_e: abiotic depletion of elements; ADP_f: abiotic depletion of fossil; AP: acidification potential; EP: eutrophication potential; FAETP: freshwater aquatic ecotoxicity potential; GWP: global warming potential; HTP: human toxicity potential; MAETP: marine aquatic ecotoxicity potential; ODP: ozone layer depletion potential; POCP: photochemical ozone creation potential; TETP: terrestrial ecotoxicity potential.]

Table 11: Water footprint of different fuels and electricity options (Clark et al., 2013; Goodwin et al., 2014; Laurenzi and Jersey, 2013; Mekonnen et al., 2015; Scanlon et al., 2014).

Fuel	**Water footprint (m^3/TJ)[a]**	**Water intensity (m^3/TJ)[b]**
Shale gas	9-90	3-14
Conventional gas	1.4-3.9	6
Conventional oil	22-601	11-172
Shale oil	162-1,580	-
Oil sands	337-1,050	60-147
Coal	17-674	4-69
Uranium	19-569	4-69
Biomass	52,000-535,000	11,000-125,000

[a] Comprises the volume of fresh water (surface, ground and rain) and volume of water polluted.
[b] The ratio of net water consumption to net energy recovery.

To mitigate the impact of water consumption, the development of regionally appropriate solutions is important. This may include regulating water withdrawals, using brackish water instead of freshwater and recycling/reusing water (Grant and Chisholm, 2014; Mauter et al., 2014; Rahm and Riha, 2012; Wang et al., 2014).

3.2.2. Water contamination

Hydraulic fracturing is carried out using a fracturing fluid, which is typically a mixture of water, sand and chemical enhancers (Figure 7). The latter is used to improve the fluid's performance, for instance, preventing scale and corrosion in the well casing and maintaining the fluid's viscosity (Cuadrilla Resources, 2017). Friction reducers, such as surfactants and polymers (natural and synthetic), make up the majority of the chemical components used in fracturing fluids and are used to reduce the friction of the fluid, so that it can be pumped in at a lower pressure while maintaining a high flow rate. Biocides (applied to kill bacteria in the water), on the other hand, are used in lower concentrations but are more hazardous (Cuadrilla Resources, 2017; FracFocus, 2014; Thurman et al., 2014). However, all chemicals are toxic to some extent, although some are much more hazardous than others (Table 12).

The use of biocides (e.g., glutaraldehyde and quaternary ammonium chloride) and acids (e.g., hydrochloric and formic) in fracturing fluids are a cause for concern to the public because of possible contamination of water sources (Moore et al., 2014). In the UK, disclosure of the composition of fracturing fluid is compulsory and this information must be made available on operators' websites (Cuadrilla Resources, 2011). In the US, it is voluntary and data are stored in the national chemical registry for fracturing fluid (FracFocus, 2015). However, although US operators disclose this information, patented chemicals are protected, which means that they can be listed as 'Trade Secret' (Gamper-Rabindran, 2014; State of Louisiana Department of Natural Resources, 2011).

Studies assessing the toxicity of fracturing fluid are scarce and, to the author's knowledge, only four have been carried out to date. Material safety data sheet information and the European Union's Regulation No. 1272/2008 have been used to assess the toxicity (Colborn et al., 2011; Gordalla et al., 2013). Hazard indices can also be calculated for different chemical formulae, providing a useful way of assessing the contribution of each component to the overall toxicity (with biocides being a major contributor); this, in turn, allows for less toxic formulations to be produced and used (Riedl et al., 2013; Schmitt-Jansen et al., 2012).

Table 12: Common chemicals used in fracturing fluid (FracFocus, 2014).

Chemical	**Purpose**	**Hazard**
Hydrochloric acid	Dissolves mineral and initiates rock fractures	Corrosive and toxic
Polyacrylamide	Reduces friction of fluid	Harmful and toxic
Ethylene glycol	Reduces friction of fluid	Harmful and carcinogenic
Ammonium persulphate	Delays breakdown of the fluid	Oxidising and toxic
Sodium chloride	Delays breakdown of the fluid and prevents clay swelling	Irritant
Methanol	Prevents pipe corrosion and reduces friction of fluid	Flammable and toxic
Formic acid	Prevents pipe corrosion	Flammable and corrosive
Glutaraldehyde	Kills bacteria in the water	Corrosive and toxic
Quaternary ammonium chloride	Kills bacteria in the water	Corrosive

In addition to fracturing fluid, drilling fluid is also used to extract shale gas and is more toxic because of the large quantities of substances, such as barite, that it often contains (Colborn et al., 2011). However, the volume of drilling fluid is small in comparison to the volume of fracturing fluid: 750-7,600 m^3 versus 3,000-21,000 m^3 (Caenn et al., 2011; Jiang et al., 2014).

The spent fracturing fluid and produced water (water contained within the gas reservoir) become wastewater, commonly referred to as flowback water. This has been found to be more problematic than fracturing fluid because it contains dissolved materials such as naturally occurring radionuclides (NORMs) and bromide (Gordalla et al., 2013). However, the concentration of NORMs in flowback water is lower than in other sources (e.g. in the medical and mining sectors) and is normally not considered to be hazardous to human health (Almond et al., 2014). Nevertheless, because the composition and concentration of NORMs depend on the mineralogy of the shale formation, it is important to understand the relationships between different groups of elements to the mineralogy; this allows more accurate predictions of water contamination associated with shale gas extraction (Chermak and Schreiber, 2014).

Water contamination associated with flowback water can occur if it is treated in a conventional wastewater treatment plant. This is because the chemicals used in fracturing fluid, as well as the high levels of bromide and total dissolved solids in produced water, are not normally handled in conventional wastewater treatment plants. This could result in chemical reactions between the chemical components and disinfectant agent in the treatment plant, leading to the formation of unwanted disinfectant by-products and an overload of existing infrastructure, as the quantity and chemical content of the wastewater exceed existing processing capacity and capability (Grant and Chisholm, 2014; Parker et al., 2014; Schnoor, 2014; Vikram et al., 2014). The latter would likely result in wastewater not being fully treated, which, if discharged into rivers, could affect toxicity and nutrient levels in aquatic and terrestrial ecosystems. These problems could be made worse by any reuse or recycling of water, which may be practiced to reduce water usage (as mentioned in the previous section). One way of getting around this would be to treat the water onsite through desalination prior to reuse, but this has cost implications (Shaffer et al., 2013).

Another source of water contamination is from hydraulic fracturing itself, with fracturing fluid and/or produced water traveling through the fracture network to groundwater and surface water bodies. However, the probability of a fracture created during hydraulic fracturing extending from the shale layer upwards to an overlying water aquifer is considered to be low; this is because the shale layer is typically 2,100 m below the surface, whereas the maximum height of an upwardly propagating hydraulic fracture is around 600 m (Davies et al., 2012).

Nevertheless, cases of water contamination have been reported and three routes of exposure identified: stray gas; spills, leaks and illegal dumping/disposal; and accumulation in disposal sites (Vengosh et al., 2014). However, research into the relationship between shale gas activity and water contamination is conflicting and inconclusive as different studies have both found and refuted a relationship (Boyer et al., 2011; DiGiulio et al., 2011; Orem et al., 2014). Elevated concentrations of chemicals, including heavy metals, have been found in drinking water wells in active shale plays (see Table 13), but the results have been critiqued (and rebutted) because of inconsistencies in datasets and data sample sizes (Fontenot et al., 2014; Fontenot et al., 2013; McHugh et al., 2014). Methane and produced water contamination have also been found and linked to faults in well integrity and cementing (Davies et al., 2014; Fontenot et al., 2013; Osborn et al., 2011; Vengosh et al., 2013; Warner et al., 2012). However, this has also been countered, because of disputes over the origin, with pre-existing networks from old oil and gas wells complicating the assessments (Davies, 2011; Jackson et al., 2013; Molofsky et al., 2011; Osborn et al., 2011; Vengosh et al., 2013; Warner et al., 2012).

It has been established with noble gas tracers that faulty well casing and cementing are a cause of groundwater methane contamination (Darrah et al., 2014). It has also been found that pre-existing fractures are not a pathway for (significant) produced water migration (Kohl et al., 2014). This was supported by a review of onshore and offshore oil and gas wells, which found that failures in well integrity caused water contamination (Davies et al., 2014).

Table 13: Chemicals found in groundwater in active US shale gas plays (Edstrom Industries, 2003; Fontenot et al., 2013; Orem et al., 2014; Osborn et al., 2011; Oram et al., 2011).

Chemical	**Detected concentration**	**Water safety limits (US)**[a]
Methane	0.30-50-40 mg/L	2 mg/L
Total organic carbon	1.20-5,804 mg/L	0.05 mg/L
Arsenic	2.20-161.20 µg/L	10 µg/L
Total dissolved solids	200-1,900 mg/L	500 mg/L
Strontium	66.20-18,195 µg/L	4,000 µg/L
Selenium	10-108.70 µg/L	500 µg/L
VOCs	Below detection limit	5 µg/L to 10 mg/L
Radon[b]	775.10 pCi/L	15 pCi/L

[a] Source: Edstrom industries.
[b] Picocuries.

One additional subject that is particularly unclear is the situation regarding abandoned and orphaned wells (Davies et al., 2014). This is important because these wells are more likely to be ill plugged and decommissioned, as it is not clear who is in charge of the abandonment activities and end-of-life monitoring to ensure their integrity has not been compromised.

In summary, existing literature provides an inconclusive evaluation of the effect of shale gas on water contamination. On one hand, evidence exists of contamination and chemicals greatly exceeding safety limits near active shale plays. On the other hand, this is unlikely to have originated from proper industrial practice and may or may not be associated with prior unrelated activity (few baseline data comparisons). One suggested approach that would greatly increase clarity in this area is to use boron and lithium fingerprinting to determine whether contamination is due to hydraulic fracturing (Davies, 2011; Warner et al., 2014).

Despite the high uncertainty over whether shale gas is likely to cause water contamination, a range of mitigation strategies could be used to prevent it (Wang et al., 2014). Baseline data, continuous monitoring over the well’s lifetime and adaptive management can reduce the likelihood of exposure, while chemical fingerprinting can be used to identify the source of contamination (Grant and Chisholm, 2014; Warner et al., 2014; Rahm and Riha, 2014). Given public concerns over this issue, greater transparency must be exercised, particularly in relation to the composition of patented chemicals in fracturing fluids.

3.2.3. Impacts from water contamination

As discussed in the previous section, there are several exposure routes by which water could be contaminated during hydraulic fracturing. In addition, water is polluted by other activities in the life cycle, leading to various impacts on aquatic organisms. These include eutrophication as well as freshwater and marine eco-toxicity. As for the air related impacts, only one LCA study has considered water related impacts of shale gas on a life cycle basis and their findings are discussed next.

As shown in Figure 11, the estimated eutrophication potential (EP) of electricity from shale gas, in the central case, is broadly comparable to conventional gas lying between offshore wind and solar PV. In the worst case, it is on par with coal and is four to 71 times worse than nuclear power, wind and solar PV. In the best case, the impact from shale gas is three times higher than nuclear power. The NO_x emissions from diesel generators used for drilling and other equipment is the biggest contributor to the EP. The next highest contributor is the disposal of drilling waste because of phosphorus (naturally occurring in soil) being extracted during drilling.

Freshwater and marine ecotoxicities are also largely caused by the disposal of drilling waste on land (common practice, as discussed in the next section). This is mainly due to the chemical stabilisers used in drilling fluids. However, when assuming the worst case, the freshwater ecotoxicity potential of shale gas electricity is over two times lower than coal (Figure 11). In the central and best cases, shale gas is comparable to conventional gas and is up to an order of magnitude better than nuclear power, offshore wind and solar PV.

A similar pattern is found when comparing shale gas electricity to the other options for marine ecotoxicity: nuclear power, offshore wind and solar PV are 1.6-7.8 times worse in the central case, while coal is 45 times worse. On the other hand, shale gas is five times worse than conventional gas (central case in Figure 11). In the worst case, it is still better than coal, but up to 10 times worse than the other options.

3.3. Land use and impacts

The impacts to land relevant to shale gas are land use, terrestrial ecotoxicity and earthquakes, as discussed below.

3.3.1. Land use

To construct a gas well, an area of land needs to be cleared to place the equipment and allow access to the drilling site. The area needed for this will depend on the site, but typically 2-3 ha (1 ha = 10^4 m^2) of land is required per well pad (AMEC, 2013). By comparison, an open-pit coal mine takes up 2,000-3,000 ha, a wind farm with 20 turbines requires 0.6-28.5 ha and a solar farm takes up 0.4-40.5 ha (Denholm et al., 2009; RenewableUK, 2015; Singh, 2004; Solar Trade Association, 2015). Thus, the area occupied by shale gas is comparable to those of wind and solar and significantly smaller than coal.

As mentioned in Section 3.1.1, the above activities will inevitably lead to LUC, causing changes to vegetation and possibly fragmentation of woodland and forest, in turn, affecting surface runoff (Slonecker et al., 2012; Soeder et al., 2014). Furthermore, depending on the site, roads may have to be constructed to allow equipment and materials to be transported (Moore et al., 2014; RSPB, 2014). All of this may also affect local ecology, but the effects are still largely unknown, apart from a few studies. For example, one study has suggested that specialised species and habitats around well pads are most at risk because of land and food-chain fragmentation (Brittingham et al., 2014). It has also been found that noise pollution from compressors at well sites affects animal behaviour (Barber et al., 2010; Barber et al., 2011). Although such studies can help with mitigation plans, certain activities and characteristics are unique to the region where shale gas extraction is taking place, making it difficult to foresee all ecological impacts.

The area occupied for shale gas extraction can be reduced through the use of multi-well pads, which have a surface footprint (and water use) per well two to four times lower than that of single-well pads (Manda et al., 2014). Reducing the surface footprint also helps to reduce depletion of abiotic resources, such as metals and minerals, required for the construction of wells (Stamford and Azapagic, 2014). However, the area available for shale gas extraction will depend on nearby land uses, as well as on policies such as setback distances, which can reduce the actual area available by as much as 31% (Blohm et al., 2012). This could lead to patches of land, rather than whole areas, being available for drilling subsequently worsening habitat fragmentation through the combined effects of the patches themselves and their associated roads for transport to and from the site.

3.3.2. Terrestrial eco-toxicity

A further issue associated with shale gas extraction is terrestrial eco-toxicity, largely because of the disposal of the drilling waste, which contains toxic components such as barite. Landfilling and land spreading are the most common routes, with the latter involving the spreading of waste onto agricultural land. The LCA study mentioned previously found that the terrestrial eco-toxicity potential of electricity from shale gas, in the central case, is 26 times higher than conventional gas. This impact is also higher for shale gas than electricity from coal, nuclear power, wind and solar PV by two to 4.5 times (see Figure 11). This is mainly due to the land spreading of drilling waste and the subsequent deposition of heavy metals and barium into soil. In the worst case, shale gas is 33-428 times worse than the other options. However, if the drilling waste is landfilled, terrestrial eco-toxicity is around a third lower than LNG and an order of magnitude lower than solar PV, offshore wind and coal. These results indicate the importance of sustainable waste management for reducing the terrestrial eco-toxicity potential of shale gas.

3.3.3. Earthquakes

The induction of earthquakes from shale gas activities has raised a lot of public concern (Koppelmann et al., 2012). Tremors are believed to be caused by fractures created during hydraulic fracturing extending to pre-existing stress lines in the rock, resulting in a slip (Johri and Zoback, 2013). However, as seen in Table 14, they are not unique to shale gas in the oil and gas industry. They are also much smaller in magnitude than those related to other activities, for example, coal mining and reservoir impoundment for hydroelectric projects. The magnitude of the tremors caused by hydraulic fracturing is such that they are typically not felt or felt but cause little damage. Similarly, the number of recorded tremors is much smaller than that for other activities, with three earthquakes having been caused by shale gas activities; British Columbia (Canada), Lancashire (UK) and Oklahoma (US) (Davies et al., 2013; Hitzman et al., 2012).

However, an increase in shale gas activity could worsen the risk of further earthquakes as a recent study found a link between the increase in the frequency of wastewater injections and the frequency and magnitude of earthquakes (Rubinstein et al., 2014). This could lead to negative impacts to the natural environment and people through damage to property and habitats, as well as distress and anger to the people affected (van der Voort and Vanclay, 2015). Despite this risk, anthropogenic earthquakes can be mitigated through the use of seismic monitoring. One such use is in the form of a traffic-light monitoring system (Table 15), through which tremors are constantly measured during hydraulic fracturing and onsite activity is directed accordingly.

Table 14: Magnitude of earthquakes induced or believed to have been caused by human activities by shale gas fracturing and other industrial activities (Davies et al., 2013).

Activity	**Measured magnitude**[a]
Hydraulic fracturing for shale gas	$1.0 \le M_L \le 3.8$
Mining (coal etc.)	$1.6 \le M_L \le 5.6$
Oil and gas field depletion	$1.0 \le M_L \le 7.3$
Water injection for secondary oil recovery	$1.9 \le M_L \le 5.1$
Reservoir impoundment	$2.0 \le M_L \le 7.9$
Waste disposal	$2.0 \le M_L \le 5.3$
Academic research boreholes	$2.8 \le M_L \le 3.1$
Solution mining	$1.0 \le M_L \le 5.2$
Geothermal operations	$1.0 \le M_L \le 4.6$

[a] M_L:local magnitude, also referred to as the Richter magnitude. Magnitudes are measured magnitudes.

Table 15: Traffic-light system for monitoring the potential for earthquakes recommended by the Royal Academy of Engineering (Koppelmann et al., 2012).

Colour	**Magnitude**	**Action**
Green	$M_L<0$	Continue activities.
Amber	$0 \le M_L \le 1.7$	Continue but under caution; injection rate may be reduced until seismicity reduced.
Red	$M_L>1.7$	Activities stopped.

4. Social aspects

Social impacts from shale gas activity vary widely, but are closely related to the economic and environmental impacts discussed in the previous sections. The following key social aspects are examined: creation of employment, health and safety and public perception.

4.1. Creation of employment

The total number of jobs created by shale gas clearly depends on the scale of activity. A single-well pad generates, on average, 20-30 direct jobs, but indirect and induced employment in the supply chain and other sectors have been estimated to be much larger, as discussed in Section 1 with respect to employment in the US (Regeneris Consulting, 2011). In the UK, it is estimated that the annual number of direct jobs will peak at 6,100, with 32,000-74,000 jobs created in total (AMEC, 2013; Lewis and Taylor, 2012; Lewis et al., 2014; Taylor and Lewis, 2013). To put this into perspective, the latter is roughly enough to reduce the UK's unemployment by between 1.5-3.4% (ONS, 2014). This is similar to the experience in the US where around 150,000 were employed in the shale gas industry (production stage) in 2010, which is equivalent to 1% of the then unemployed population (U.S. Census Bureau, 2012).

The average salary in the industry is high, with workers earning £36,000-£160,000 (Lewis et al., 2014). Together with the creation of jobs, this can potentially benefit local areas where shale gas is produced. However, this is assuming specialised and experienced workers are locally available. This may not necessarily be the case, so workers may need to be brought in from elsewhere. This is also the case in the US, where workers are brought in from other states and instead of relocating, commuted long distances between home and work (Jacquet, 2014; Schafft et al., 2014).

In addition, the generation of new employment in shale gas could help with gender inequality issues endemic in the oil and gas industry: for example, in the UK female employees make up only 3.7% of the total workforce in this sector. In Australia it is 13% and in Canada 21% (McGrath and Marinelli, 2012; Oil & Gas UK, 2011). By contrast, in the US 46% of new oil and gas jobs were filled by women in 2013 (Czebiniak, 2014). In spite of this, there have been no studies to examine in more detail issues related to employment equality.

4.2. Health and safety

The production of shale gas can pose a risk to well site workers, as well as people living close by and elsewhere in the supply chain, when considering a life cycle perspective. Safety risks to workers include accidents onsite, ranging from minor injuries to fatalities. In comparison to other industries, based on the records for the US and UK, the oil and gas industry (including shale gas) has a lower accident rate than mining, construction and agriculture (Bureau of Labor Statistics, 2015; HSE, 2015). This is because of stringent safety regulations and measures put in place in these countries to ensure the safety of workers at oil and gas sites (OGP, 2013). However, in some other regions, particularly in developing countries, safety records and regulations may not be as good and worker safety remains a concern. Beyond the site boundaries, safety risks to people living close by include accidents related to increased traffic around the site as well as explosions and fire in case of operational failures (Graham et al., 2015).

The health risks to workers on well pad sites are well documented and include silica exposure, inhalation of gases, such as VOCs, NO_x and H_2S, as well as exposure to noise (Mulloy, 2014). These risks, in particular silica and gas inhalation, can lead to chronic illnesses, such as chronic obstructive pulmonary disease, lung cancer and cardiovascular problems (HSE, 2013; MDH, 2015; United States Department of Labor, 2015). However, these are caused by long-term exposure, so are less likely to occur if proper measures are taken to protect workers. Acute illnesses, on the other hand, are more likely to occur as they are caused by short-term or accidental exposure. Acute ailments include dizziness, headaches and eye and respiratory irritation (HSE, 2013; MDH, 2015; United

States Department of Labor, 2015). These risks can be mitigated by implementing appropriate measures, such as personal protective equipment and using efficient equipment onsite. However, accidents can still happen despite protective measures, as demonstrated by recent fatalities on US shale gas well sites that occurred during equipment testing and maintenance work (Arenschield, 2014; Garcia, 2014; Mulloy, 2014).

The health risks to workers are also applicable to residents living close to well sites, but quantitative studies on the impacts to public health are lacking in the literature. As a result, there is little guidance available on how to mitigate risks to residents living in close proximity to well sites. On the other hand, qualitative studies on perceived health impacts abound, which suggests that there is a link between ill health and shale gas production (Ferrar et al., 2013; Rabinowitz et al., 2014; Steinzor et al., 2013), with people surveyed reporting a wide variety of physical (nausea, nosebleeds and headaches) and mental (stress and anxiety) ailments (Table 16). Stress and anxiety have been commonly associated with oil and gas production, but often because residents felt that they are not being listened to (Ferrar et al., 2013; Rabinowitz et al., 2014; Steinzor et al., 2013; van der Voort and Vanclay, 2015). Thus, it seems that certain health problems may be related to communication, engagement and perception rather than physical phenomena. However, most studies are based on self-reported surveys with no professional medical diagnosis of symptoms. The sample sizes are also small and the studies have been conducted over short periods. Thus, long-term studies on the effects of shale gas production on human health are still needed as there are many uncertainties and unanswered questions (Jackson et al., 2014).

Table 16: Health symptoms reported by residents living closed to shale gas wells (Ferrar et al., 2013; Rabinowitz et al., 2014; Steinzor et al., 2013).

Physical symptoms	**Mental symptoms**
Rashes, sores and blisters	Depression
Burning eyes	Difficulty concentrating
Joint swelling and muscle aches	Memory loss
Headaches	Sleeping difficulties
Coughs	Anxiety
Dizziness and chest pains	Stress
Nose bleeds	

There have been no fatalities among residents living near well pads, but there have been numerous reports of pet and livestock deaths as well as birth abnormalities in farm animals (Bamberger and Oswald, 2012; Lisak, 2015). This is important because bioaccumulation is a risk/exposure pathway as it is possible for toxins to build up and travel up through the food chain, which could affect humans. However, currently there is a lack of studies that consider these aspects.

On a life cycle basis, the LCA studies mentioned earlier found that, in comparison to coal and solar PV, electricity from shale gas has a lower human toxicity potential, by 6.6-10.6 times (Figure 11) (Stamford and Azapagic, 2014). It is only in the worst assumed case that shale gas exceeds the human toxicity potential of coal power (by 17%). As for the other ecotoxicities, the main cause of this impact is land spreading drilling waste owing to the toxicity of barite.

4.3. Public perception

Public perception has been identified as a major obstacle in shale gas development (House of Lords, 2013), but it is difficult to measure robustly because it can be influenced by many factors. For example, survey results in the UK have found awareness, measured as the number of people who know what shale gas and hydraulic fracturing are, to have increased in recent years (Figure 12), but results are conflicting and inconclusive (Castell et al., 2014; DECC, 2015; O'Hara et al., 2015). This is because many people associate shale gas with earthquakes, water contamination and cheap energy. However, many people are unsure of its GHG emissions and whether or not it can be described as a 'clean' energy source. The survey data indicate that there is public support for shale gas, which could be linked to the association with cheap energy. On the other hand, surveys also identified that a large proportion of people are unsure of their stance, being neither for, nor against it (Castell et al., 2014; O'Hara et al., 2015).

Conversely, similar surveys in the US have found that the majority of Americans are unfamiliar with shale gas, being either unclear on what it is or completely unaware of it (Boudet et al., 2013). However, this could be because the US is much larger than the UK, as results varied from state to state (Boudet et al., 2013). States with a history in oil and gas, such as Texas and Pennsylvania, typically have a higher proportion of people in favour, whereas states such as New York, New Jersey and California, which do not have a related history, are more likely to oppose shale gas development (Carroll, 2014; Eaton, 2013; Freyman and Salmon, 2013; Rahm, 2011).

The high uncertainty and variation in public stance could be the result of media coverage. Anti-fracking protesters and demonstrations have featured heavily in the media, such as the Barton Moss and Balcombe protests in the UK and the demonstrations in southern Algeria, which could have affected public opinions about shale gas (Gall, 2015; Tarver, 2013). In some countries, the coverage is balanced, with both pro and anti-shale gas stories being covered. However, in others it is polarised, for example, in Poland, where media depiction is strongly pro-shale gas (Jaspal et al., 2014). An interesting finding is the connotation associated with the word ‘fracking’, which is frequently used by the media. The word has been found to have negative meaning, whereas ‘hydraulic fracturing’ is more neutral, which suggests that media can unknowingly influence perceptions (Climek et al., 2013; Evensen et al., 2014; Muehlenbachs et al., 2013).

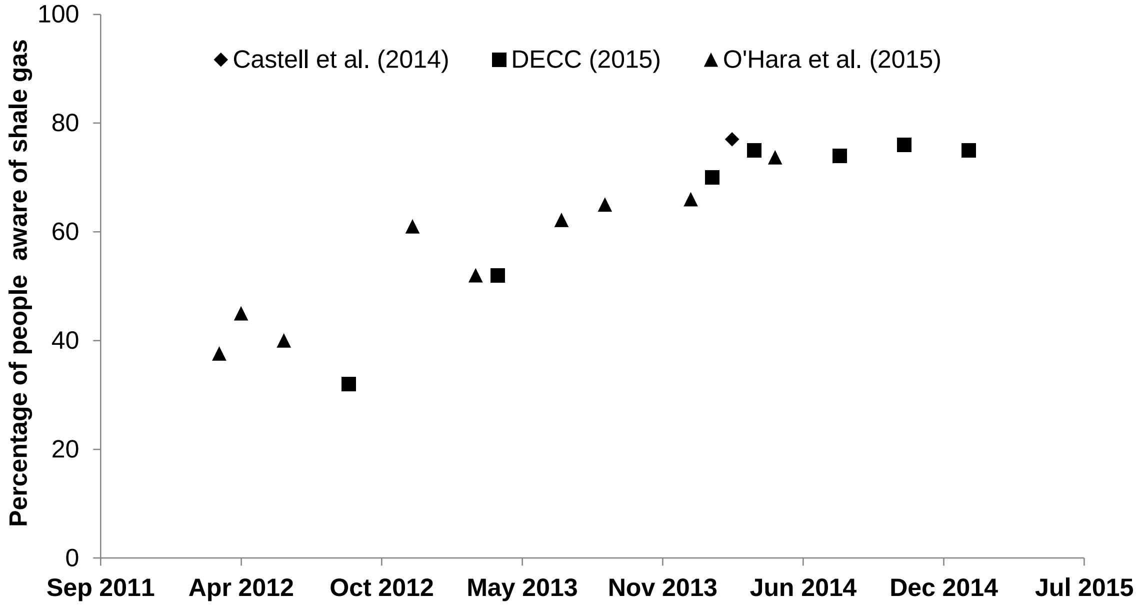


Figure 12: Public awareness of shale gas in the UK (Castell et al., 2014; DECC, 2015; O'Hara et al., 2015).

The way shale gas is regulated will affect public attitudes and willingness to accept it. In many countries, existing oil and gas regulations are currently thought to be sufficient, but new legislation is being introduced to tackle problems associated with shale gas that have arisen or could arise. However, the introduction of new legislation takes time. In March 2015, the Obama administration issued new federal regulations for hydraulic fracturing but this comes nearly 10 years after the shale gas ‘boom’ (Davenport, 2015). Similarly, the UK Government revised its Infrastructure Bill in late 2014 to include legislation for hydraulic fracturing, but this is four years after the first shale gas well was drilled (Baroness Kramer, 2014; HM Government, 2015). Moreover, existing and newly proposed regulations have been criticised by parties from both sides of the argument, with industry arguing that they will slow down the rate of drilling and environmental groups arguing they are not doing enough to protect people and the environment. Therefore, it is important that shale gas is regulated in a way that meets the expectations of all stakeholders.

Given the importance of regulation for public perception, an effective shale gas industry requires full compliance with regulations and oversight by independent regulatory bodies. Loopholes in regulation and self-regulating are not seen favourably by the public. The former includes protection from the disclosure of patented chemical used for hydraulic fracturing in the US, which was strongly criticised by environmental groups (House of

Lords, 2014). Similarly, amendments to EU and UK legislation to try to close loopholes have been met with disapproval: in the EU, legislation exempted shale gas from tougher environmental rules (it does not fall under all relevant permits) and in the UK, the Infrastructure Bill was recently amended to allow *"passing any substance through, or putting any substance into deep-level land or infrastructure installed in deep-level land"*, which enables operators to use any chemicals they wish. Both of these have received fervent criticism from environmentalists (Baroness Kramer, 2014).

This is why it is crucial that public engagement and communication is carried out carefully, avoiding miscommunication and building trust. Shale gas remains a sensitive issue and the fact that some people hold very strong, inflexible views either for or against it needs to be taken into account (Raimi and Leary, 2014). Governments and industry in countries new to unconventional onshore oil and gas will have to work harder if they want to win public support as they have no previous experience in the industry and the public is unsure of what to expect. As discussed above, evidence from the US suggests that regions with a track record in onshore extraction tend to show greater acceptance. It may be appropriate for some of these countries to integrate shale gas development plans into large schemes and plans, such as national energy goals (House of Lords, 2013). This could be beneficial as it would put shale gas into a broader context so that people can see how it fits in with the country's energy needs.

5. Further discussion and policy implications

Overall, shale gas has had a considerable impact on the US economy, particularly on gas prices and the reinvigoration of its chemicals and manufacturing industries (EIA, 2014b; PwC, 2011). These economic benefits are one of the main drivers for other countries wanting to exploit their shale gas resources, but many face issues associated with lack of experience in onshore gas production and particularly hydraulic fracturing. Therefore, it is uncertain whether other countries could replicate the economic success of the US, as it is likely that large capital investment and extensive R&D would be needed to develop the industry successfully on a commercial scale. As suggested in the literature, it may be that it is still too early for some countries to develop the resource as investment may exceed the revenue generated (Table 10).

Similar to most extractive processes, shale gas is associated with many environmental issues. However, the majority of existing literature considers shale gas alone rather than in comparison with other fuels. This should be a key area of future focus, as the impacts associated with hydraulic fracturing are not unique to it. Coal mining, for instance, has been known to induce seismic tremors; its tailings and other waste products are also toxic. Canadian oil sands have led to forest fragmentation and habitat loss because of dynamite charges (for seismic surveys), road construction and other mining processes (Woynillowicz, 2007). Conventional oil and gas extraction has been associated with water contamination and hydraulic fracturing can be used in conventional wells to increase productivity. Air pollutants are also associated with conventional gas production as conventional and shale gas production differs only in horizontal drilling and hydraulic fracturing.

This suggests that many of the major environmental issues associated with shale gas extraction can be mitigated, if not prevented (Jackson et al., 2014; Wang et al., 2014). The use of best practice and BAT, as opposed to standard practice, can help to protect people and the environment (Uth, 2014). Developments in policy and practices could then be used and adapted in mitigation schemes in different countries, as well as for new related energy technologies. The latter might include, for instance, enhanced geothermal systems, which involve hydraulic fracturing and carbon capture and sequestration, which has been linked to CO_2 emissions from its migration to the surface through fractures and channels in the rock (Moors, 2014).

Shale gas has the potential for substantial positive socioeconomic impact. This includes significant direct and induced employment, which could give a large boost to local communities, provided that workers are not imported from elsewhere. This boost in employment could also help with equality issues, such as gender, ethnicity and age. However, there are a number of interrelated barriers that need to be addressed, including environmental impacts as well as public perception, understanding and engagement (House of Lords, 2013). There are many stakeholders involved in the supply chain, which makes compromising complex as not everyone will be happy with the end result. More research into understanding the impacts on human health and public opinion is needed, especially outside the US and EU.

The economic, environmental and social implications of shale gas extraction-as summarised above-are all deeply influenced by policy. Therefore, it is important that appropriate legislation is implemented and is reinforced and regularly reviewed. Had policy and regulations in the US been more stringent in the early days of shale gas development, it is possible that many of its impacts and some public opposition that followed in other countries might have been prevented. For example, the exclusion of hydraulic fracturing from the Safe Drinking Water Act in the US fuelled concerns of water contamination by toxic chemicals, as it exclusion means that chemicals used in hydraulic fracturing are not regulated (Gamper-Rabindran, 2014). On the other hand, the US Government’s role in initial R&D through the Unconventional Gas Research Program (1976-1992) and the Eastern Gas Shale Project (1976-1997) helped to develop domestic skills, technology and research (Wang and Krupnick, 2013b; Wang and Krupnick, 2013a).

Therefore, the US experience could be useful for other countries in formulating shale gas policies to avoid the negative impacts of shale gas development and improve public perception.

However, the geographical abundance that makes shale gas an attractive option in terms of energy security also leads to difficulties in creating a standard set of policies: each country and region in possession of reserves has different oil and gas production history, geography, geology and economic circumstances. Despite this, there are specific polices that could be homogeneous in many of these countries, such as long-term monitoring of air and water quality, as well as gathering good baseline and background data for all potential exploration sites. The disadvantage of such recommendations is, of course, the time and expense required: if the owner/operator must pay, this may put off many from investing in what is already a high-risk venture. Therefore, there is a need for collaboration between industry, government and academia to collect data and communicate with the public. There is also a need for more adequate funding to strengthen the implementation of regulation and prevent understaffing of regulators.

Additionally, it is important to include shale gas in long-term energy policies, particularly because recent years have seen international shifts in energy policies toward the reduction of GHG emissions (UNEP, 2012). For many countries, this means reducing coal capacity and increasing gas, but this does not necessarily translate into reduced GHG emissions: if gas were to replace renewable and nuclear capacity, then the benefits would be negated. For this reason, policies and incentives must be put in place to develop other low-carbon energy sources alongside any shifts in gas (Bistline, 2014; Newell and Raimi, 2014). In a global shale-boom scenario, it is also possible that overall energy consumption could increase (the ‘rebound’ effect), again negating any emission reductions. Therefore, shale gas can only be exploited within a cogent framework of climate change mitigation policies.

Many new regulations that have been introduced are economically motivated because most governments believe current environmental legislations for conventional oil and gas are sufficient (Government of Alberta, 2014; European Commission, 2014). However, this has been countered by many arguing that the extent of hydraulic fracturing and other unique activities cannot be managed with current legislation because it predates shale gas exploitation.

6. Conclusions

This review has considered the economic, environmental and social sustainability of shale gas. The findings suggest that significant sustainability trade-offs may be needed if shale gas were to be developed on a large scale, but some of this may be due to uncertainties because of a lack of data. Despite the uncertainties, some facts associated with shale gas development are well established. For example, poor well integrity, faulty or inadequate equipment and poor regulation are the cause of many of the sustainability impacts; these issues can be resolved by the implementation of best practice and BAT, whereas better regulation of activities and improved transparency can ease social concerns and help to build trust.

The impact of shale gas on the US economy has been significant as a result of lower energy prices. However, many countries with shale gas reserves lack the skills, knowledge and infrastructure of the US, leading to doubts about the economic viability of shale gas outside the US. This uncertainty is also mirrored in social acceptance and perception. Other social impacts associated with it are unclear because studies on topics such as employment opportunities, human health and public engagement are limited and often specific to the US. There is, however, more information on the environmental impacts which have been researched more extensively.

In the meantime, this much is clear: the future of global shale gas development will depend on a combination of the industry demonstrating environmentally sustainable practice, the level of political will to see development through to maturity and public support, with the latter most likely being the biggest determinant.

References

ACC. **2011**. *Shale gas and new petrochemicals investment: Benefits for the economy, jobs, and US manufacturing*. October, 2014. *American Chemistry Council (ACC)*. Washington DC. Retrieved from: http://chemistrytoenergy.com/sites/chemistrytoenergy.com/files/ACC-Shale-Report.pdf.

Allen, D. T., Torres, V. M., Thomas, J., Sullivan, D. W., Harrison, M., Hendler, A., Herndon, S. C., Kolb, C. E., Fraser, M. P., Hill, A. D., Lamb, B. K., Miskimins, J., Sawyer, R. F. and Seinfeld, J. H. **2013**. Measurements of methane emissions at natural gas production sites in the United States. *Proceedings of the National Academy of Sciences*, 110, 17768-17773.

Almond, S., Clancy, S. A., Davies, R. J. and Worrall, F. **2014**. The flux of radionuclides in flowback fluid from shale gas exploitation. *Environmental Science and Pollution Research*, 21, 12316-12324.

AMEC. **2013**. *Strategic environmental assessment for further onshore oil and gas licensing*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/consultations/environmental-report-for-further-onshore-oil-and-gas-licensing.

Andrews, I. J. **2013**. *The Carboniferous Bowland Shale gas study: geology and resource estimation*. *British Geological Society (BGS)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/226874/BGS_DECC_BowlandShaleGasReport_MAIN_REPORT.pdf.

Anirban, R. A., Adams, P. J. and Robinson, A. L. **2014**. Air pollutant emissions from the development, production, and processing of Marcellus Shale natural gas. *Journal of the Air and Waste Management Association*, 64, 19-37.

Arenschield, L. **2014**. Worker killed in explosion at Nobel County oil and gas facility. *The Columbus Dispatch*, November 14, 2014, Available from: http://www.dispatch.com/content/stories/local/2014/11/13/Worker-killed-at-Noble-County-oil-and-gas-well.html.

Armendariz, A. **2009**. *Emissions from natural gas production in the Barnett Shale area and opportunities for cost-effective improvements*. January, 2014. *Department of Environmental and Civil Engineering, Southern Methodist University*. Dallas, TX, USA. Retrieved from: https://www.edf.org/sites/default/files/9235_Barnett_Shale_Report.pdf.

Arora, V. and Cai, Y. **2014**. U.S. natural gas exports and their global impacts. *Applied Energy*, 120, 95-103.

Bamberger, M. and Oswald, R. E. **2012**. Impacts of gas drilling on human and animal health. *New Solutions*, 22, 51-77.

Barber, J. R., Burdett, C. L., Reed, S. E., Warner, K. A., Formichella, C., Crooks, K. R., Theobald, D. M. and Fristrup, K. M. **2011**. Anthropogenic noise exposure in protected natural areas: estimating the scale of ecological consequences. *Landscape Ecology*, 26, 1281-1295.

Barber, J. R., Crooks, K. R. and Fristrup, K. M. **2010**. The costs of chronic noise exposure for terrestrial organisms. *Trends in Ecology and Evolution*, 25, 180-189.

Baroness Kramer. **2014**. *Infrastructure Bill*, The Stationery Office (TSO), London, UK.

Berman, A. E. and Pittinger, L. F. **2011**. US shale gas: less abundance, higher cost. [Online], 5 August. Available: http://www.theoildrum.com/node/8212 [Accessed: February 2017].

BIS. **2013**. *UK oil and gas: Business and Government action*. June, 2014. *Department for Business, Innovation and Skills (BIS)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/175480/bis-13-748-uk-oil-and-gas-industrial-strategy.pdf.

Bistline, J. E. **2014**. Natural gas, uncertainty, and climate policy in the US electric power sector. *Energy Policy*, 74, 433-442.

Blohm, A., Peichel, J., Smith, C. and Kougentakis, A. **2012**. The significance of regulation and land use patterns on natural gas resource estimates in the Marcellus shale. *Energy Policy*, 50, 358-369.

BNEF. **2013**. *The economic impact on UK energy policy of shale gas and oil*. April, 2014. *Bloomberg New Energy Finance (BNEF)*. London, UK. Retrieved from: http://about.bnef.com/white-papers/the-economic-impact-on-uk-energy-policy-of-shale-gas/.

Bolton, R. and Foxon, T. J. **2014**. A socio-technical perspective on low carbon investment challenges- Insights for UK energy policy. *Environmental Innovation and Societal Transitions*, 14, 165-181.

Bond, C. E., Roberts, J., Hastings, A., Shipton, Z. K., Joao, E. M., Kyzy, J. T. and Stephenson, M. **2014**. *Life-cycle assessment of greenhouse gas emissions from unconventional gas in Scotland*. September, 2014. *ClimateXChange*. Glasgow, UK. Retrieved from: http://www.climatexchange.org.uk/reducing-emissions/understanding-potential-climate-impact-unconventional-gas-extraction-scotland.

Bonetti, L. **2014**. *Shale gas and Germany's energiewende: A cost-benefit analysis for the power generation sector*. MSc Thesis, Norwegian School of Economics.

Boudet, H., Clarke, C., Bugden, D., Maibach, E., Roser-Renouf, C. and Leiserowitz., A. **2013**. "Fracking" controversy and communication: Using national survey data to understand public perceptions of hydraulic fracturing. *Energy Policy*, 65, 57-67.

Boyer, E. W., Swistock, B. R., Clark, J., Madden, M. and Rizzo, D. E. **2011**. *The impact of Marcellus gas drilling on rural drinking water supplies*. April, 2014. *Center for Rural*

Pennsylvania. Harrisburg, PE, USA. Retrieved from: http://www.rural.palegislature.us/documents/reports/Marcellus_and_drinking_water_2012.pdf.

BP. **2012**. *Unconventional gas and hydraulic fracturing: Issue briefing*. April, 2014. *British Petroleum (BP)*. London, UK. Retrieved from: http://www.bp.com/content/dam/bp/pdf/investors/6423_BP_Unconventional_Gas.pdf.

BP. **2014**. *BP statistical review of world energy June 2014*. *British Petroleum (BP)*. London, UK. Retrieved from: http://www.bp.com/content/dam/bp-country/de_de/PDFs/brochures/BP-statistical-review-of-world-energy-2014-full-report.pdf.

Brandt, A. R., Heath, G. A., Kort, E. A., O'Sullivan, F., Petron, G., Jordaan, S. M., Tans, P., Wilcox, J., Gopstein, A. M., Arent, D., Wofsy, S., Brown, N. J., Bradley, R., Stucky, G. D., Eardley, D. and Harriss, R. **2014**. Methane leaks from North American natural gas systems. *Science*, 343, 733-735.

Brittingham, M. C., Maloney, K. O., Farag, A. M., Harper, D. D. and Bowen, Z. H. **2014**. Ecological risks of shale oil and gas development to wildlife, aquatic resources and their habitats. *Environmental Science and Technology*, 48, 11034-11047.

Broderick, J. and Anderson, K. **2012**. *Has US shale gas reduced CO2 emissions? A research briefing commissioned by The Co-operative*. *Tyndall Centre for Climate Change*. Manchester, UK. Retrieved from: http://www.tyndall.ac.uk/sites/default/files/broderick_and_anderson_2012_impact_of_shale_gas_on_us_energy_and_emissions.pdf.

Broderick, J., Anderson, K., Wood, R., Gilbert, P. and Sharmina., M. **2011**. *Shale gas: an updated assessment of environmental and climate change impacts*. *Tyndall Centre for Climate Change and Research*. Manchester, UK. Retrieved from: http://www.tyndall.ac.uk/sites/default/files/coop_shale_gas_report_update_v3.10.pdf.

Bureau of Labor Statistics. **2015**. *Census of fatal occupational injuries (CFOI)- Current and revised data*. January, 2015. *Bureau of Labor Statistics*. Washington DC. Retrieved from: http://www.bls.gov/iif/oshcfoi1.htm.

Burnham, A., Han, J., Clark, C. E., Wang, M., Dunn, J. B. and Palou-Rivera, I. **2012**. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. *Environmental Science and Technology*, 46, 619-627.

Busch, C. and Gimon, E. **2014**. Natural gas versus coal: Is natural gas better for the climate? *The Electricity Journal*, 27, 97-111.

Caenn, R., Darley, H. C. H. and Gray, G. R. **2011**. *Composition and properties of drilling and completion fluids* 6th, Oxford, UK: Gulf Professional Publishing, Elsevier.

Carroll, R. **2014**. California City halts new oil drilling over fracking concerns. *Reuters*, March 19, 2015, Available from: www.reuters.com/article/california-fracking-idUSL2N0MG04020140319.

Castell, S., Charlton, A., Clemence, M., Pettigrew, N., Pope, S., Quigley, A., Shah, J. N. and Silman, T. **2014**. *Public attitudes to science 2014*. *Ipsos MORI*. London, UK. Retrieved from: https://www.ipsos-mori.com/Assets/Docs/Polls/pas-2014-main-report.pdf.

Caulton, D. R., Shepson, P. B., Santoro, R. L., Sparks, J. P., Howarth, R. W., Ingraffea, A. R., Cambaliza, M. O. L., Sweeney, C., Karion, A., Davis, K. J., Stirm, B. H., Montzka, S. A. and Miller, B. R. **2014**. Toward a better understanding and quantification of methane emissions from shale gas development. *Proceedings of the National Academy of Sciences*, 111, 6237-6242.

Cheng, C. **2014**. *China energy monthly report: August to October 2014*. April, 2014. *British Embassy Beijing*. Beijing, CN. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/376463/China_-_Energy_Monthly_August_to_October_2014.pdf.

Chermak, J. A. and Schreiber, M. E. **2014**. Mineralogy and trace element geochemistry of gas shales in the United States: Environmental implications. *International Journal of Coal Geology*, 126, 32-44.

Chou, E. **2013**. *Shale gas in China- Development and challenges*. *Harvard University* Cambridge, MA, USA. Retrieved from: http://blogs.harvard.edu/ellachou/files/2013/07/Shale-Gas-in-China-Draft.pdf.

Clark, C., Burnham, A., Harto, C. and Horner, R. **2013**. *Hydraulic fracturing and shale gas production: Technology, impacts, and regulations*. *Argonne National Laboratory*. Oak Ridge, TN, USA. Retrieved from: http://www.afdc.energy.gov/uploads/publication/anl_hydraulic_fracturing.pdf.

Clark, C., Han, J., Burnham, A., Dunn, J. B. and Wang, M. Q. **2011**. *Life-cycle analysis of shale gas and natural gas*. *Argonne National Laboratory*. Lemont, IL, USA. Retrieved from: https://greet.es.anl.gov/publication-shale_gas.

Clark, P. and Bounds, A. **2015**. Ministers freed to intervene in fast-track fracking drive. *Financial Time (FT)*, August 13, 2015, Available from: https://next.ft.com/content/a346b038-4114-11e5-b98b-87c7270955cf.

Climek, M., Brou, L., Means, M. and Goidel, K. **2013**. *Fracking and polarization of public opinion*. October, 2014. *Louisiana State University*. Baton Rouge, LA, USA. Retrieved from: https://sites01.lsu.edu/wp/pprl/files/2012/07/National-Fracking-Report-7-24-13-Public-Policy-Research-Lab-at-LSU.pdf.

Cluff, M. A., Hartsock, A., MacRae, J. D., Carter, K. and Mouser, P. J. **2014**. Temporal changes in microbial ecology and geochemistry in produced water from hydraulically fractured Marcellus shale gas wells. *Environmental Science and Technology*, 48, 6508-6517.

CNLG. **2014**. *Imports* [Online] Washington DC: Centre for Liquefied Natural Gas (CNLG). Available: http://www.lngfacts.org/lng-market/imports/ [Accessed 18 December 2014].

Colborn, T., Kwiatkowski, C., Schultz, K. and Bachran, M. **2011**. Natural gas operations from a public health perspective. *Human and Ecological Risk Assessment: An International Journal*, 17, 1039-1056.

Colborn, T., Schultz, K., Herrick, L. and Kwiatkowski, C. **2014**. An exploratory study of air quality near natural gas operations. *Human and Ecological Risk Assessment: An International Journal*, 20, 86-105.

Conti, J. J., Holtberg, P. D., Beamon, J. A., Napolitano, S. A., Schaal, M. and Turnure., J. T. **2013**. *Annual energy outlook 2013 with projection to 2040*. *US Energy Information Administration (EIA)*. Washington DC. Retrieved from: http://www.eia.gov/forecasts/aeo/pdf/0383%282013%29.pdf.

Cook, P., Beck, V., Brereton, D., Clark, R., Fisher, B., Kentish, S., Toomey, J. and Williams, J. **2013**. *Engineering energy: unconventional gas production*. October, 2014. *Australian Council of Learned Academies*. Melbourne, AU. Retrieved from: http://www.acola.org.au/PDF/SAF06FINAL/Final%20Report%20Engineering%20Energy%20June%202013.pdf.

Cronin, K. **2013**. *Community engagement charter oil and gas from unconventional reservoirs*. *UK Onshore Oil and Gas (UKOOG)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/256360/Publication_UKOOG_communityengagementcharterversion6.pdf.

Cuadrilla Resources. **2011**. *Composition of components in Bowland shale hydraulic fracturing fluid for Preese Hall-1 well* [Online] Linchfield, UK: Cuadrilla Resources. Available: http://www.cuadrillaresources.com/wp-content/uploads/2012/02/Chemical-Disclosure-PH-1.jpg [Accessed 5 August 2015].

Cuadrilla Resources. **2017**. *Fracturing fluid* [Online] Preston, UK. Available: http://www.cuadrillaresources.com/what-we-do/hydraulic-fracturing/fracturing-fluid/ [Accessed 2017 February].

Cylwik, A., Pietka-Kosinska, K., Lada, K. and Sobolewski, M. **2012**. *Ekonomiczny potencjal produkcji gazuscenariuszowa Polsce w latach 2012-2015. Analiza scenariuszowa*. July, 2014. *Centrum Analiz Spoleczno-Ekonomicznych*. Warsaw, PL. Retrieved from: http://www.case-research.eu/pl.

Czebiniak, M. **2014**. Women find careers in energy as downstream, petchems see growth. *Pittsborgh Post-Gazette*, August 12, 2014, Available from: http://powersource.post-gazette.com/powersource/companies/2014/08/12/Women-of-shale/stories/201408120004.

Dale, A. T., Khanna, V., Vidic, R. D. and Bilec, M. M. **2013**. Process based life-cycle assessment of natural gas from the Marcellus Shale. *Environmental Science and Technology*, 47, 5459-5466.

Darrah, T. H., Vengosh, A., Jackson, R. B., Warner, N. R. and Poreda, R. J. **2014**. Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales. *Proceedings of the National Academy of Sciences*, 111, 14076-14081.

Davenport, C. **2015**. New Federal rules are set for fracking. *The New York Times*, March 20, 2015, Available from: http://www.nytimes.com/2015/03/21/us/politics/obama-administration-unveils-federal-fracking-regulations.html?_r=0.

Davies, R., Foulger, G., Bindley, A. and Styles, P. **2013**. Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. *Marine and Petroleum Geology*, 45, 171-185.

Davies, R. J. **2011**. Methane contamination of drinking water caused by hydraulic fracturing remains unproven. *Proceedings of the National Academy of Sciences*, 108, E871-E871.

Davies, R. J., Almond, S., Ward, R. S., Jackson, R. B., Adams, C., Worrall, F., Herringshaw, L. G., Gluyas, J. G. and Whitehead, M. A. **2014**. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. *Marine and Petroleum Geology*, 56, 239-254.

Davies, R. J., Mathias, S. A., Moss, J., Hustoft, S. and Newport, L. **2012**. Hydraulic fractures: How far can they go? *Marine and Petroleum Geology*, 37, 1-6.

DECC. **2013a**. *Statistics at DECC: Energy sector statistics* [Online] London, UK: Department of Energy and Climate Change (DECC). Available: https://www.gov.uk/government/organisations/department-of-energy-climate-change/about/statistics#energy-sector-statistics [Accessed August 2015].

DECC. **2013b**. *UK energy in brief 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224130/uk_energy_in_brief_2013.PDF.

DECC. **2015**. *DECC public attitudes tracking survey: Wave 15*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/collections/public-attitudes-tracking-survey.

Denholm, P., Hand, M., Jackson, M. and Ong, S. **2009**. *Land-use requirements of modern wind power plants in the United States*. October, 2013. *National Renewable Energy Laboratory (NREL)*. Oak Ridge, TN, USA. Retrieved from: http://www.nrel.gov/docs/fy09osti/45834.pdf.

DiGiulio, D. C., Wilkin, R. T., Miller, C. and Oberley, G. **2011**. *Investigation of ground water contamination near Pavillion, Wyoming*. March, 2015. *Environmental Protection Agency (EPA)*. Washington DC. Retrieved from: http://www2.epa.gov/sites/production/files/documents/EPA_ReportOnPavillion_Dec-8-2011.pdf.

Eaton, T. T. **2013**. Science-based decision-making on complex issues: Marcellus shale gas hydrofracking and New York City water supply. *Science of The Total Environment*, 461-462, 158-169.

Edstrom Industries. **2003**. *Drinking water quality standards*. April, 2015. *Edstrom Industries*. Waterford, WI, USA. Retrieved from: www.edstrom.com/file.aspx?DocumentId=72.

EIA. **2011**. *Review of emerging resources: U.S. shale gas and shale oil Plays*. *US Energy Information Administration (EIA)*. Washington DC. Retrieved from: https://www.eia.gov/analysis/studies/usshalegas/pdf/usshaleplays.pdf.

EIA. **2013**. *U.S. energy-related carbon dioxide emissions, 2012*. October, 2013. *US Energy Information Administration (EIA)*. Washington DC. Retrieved from: http://www.eia.gov/environment/emissions/carbon/pdf/2012_co2analysis.pdf.

EIA. **2014a**. *Countries* [Online]: US Energy Information Administration (EIA). Available: http://www.eia.gov/countries/ [Accessed December 2014].

EIA. **2014b**. *Natural gas prices* [Online] Washington DC: US Energy Information Administration (EIA). Available: http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm [Accessed December 2014].

EIA. **2015**. *Spot prices* [Online] Washinton DC: US Energy Information Administration (EIA). Available: http://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm [Accessed March 2015].

Ekstrom, V. **2014**. America's leaky natural gas system needs a fix, study finds. [Online], 13 February. Available: http://mitei.mit.edu/news/americas-leaky-natural-gas-system-needs-fix-study-finds [Accessed: 13 February 2015].

European Commission. **2014**. *Recommendations: Commission recommendations of 22 January 2014 on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing*, European Commission, Brussels, BE.

Evensen, D., Jacquet, J. B., Clarke, C. E. and Stedman, R. C. **2014**. What's the 'fracking' problem? One word can't say it all. *The Extractive Industries and Society*, 1, 130-136.

Ferrar, K. J., Kriesky, J., Christen, C. L., Marshall, L. P., Malone, S. L., Sharma, R. K., Michanowicz, D. R. and Goldstein, B. D. **2013**. Assessment and longitudinal analysis of health impacts and stressors perceived to result from unconventional shale gas development in the Marcellus Shale region. *International Journal of Occupational and Environmental Health*, 19, 104-112.

Field, R. A., Soltis, J. and Murphy, S. **2014**. Air quality concerns of unconventional oil and natural gas production. *Environ. Science: Processes and Impacts*, 16, 954-969.

Fontenot, B. E., Hildenbrand, Z. L., Carlton, D. D., Walton, J. L. and Schug, K. A. **2014**. Response to Comment on ``An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett Shale formation''. *Environmental Science and Technology*, 48, 3597-3599.

Fontenot, B. E., Hunt, L. R., Hildenbrand, Z. L., Carlton Jr., D. D., Oka, H., Walton, J. L., Hopkins, D., Osorio, A., Bjorndal, B., Hu, Q. H. and Schug, K. A. **2013**. An Evaluation of Water Quality in Private Drinking Water Wells Near Natural Gas Extraction Sites in the Barnett Shale Formation. *Environmental Science and Technology*, 47, 10032-10040.

Forster, D. and Perks, J. **2012**. *Climate impact of potential shale gas production in the EU*. *AEA Technology Plc*. Didcot, UK. Retrieved from: http://ec.europa.eu/clima/policies/eccp/docs/120815_final_report_en.pdf.

Fowler, J. **2014**. *Mexico's gas market analysis webinar* [Online], 25 November. *Webinar*. Available from: http://www.icis.com/contact/mexicogaswebinarslides/.

FracFocus. **2014**. *What chemicals are used* [Online] Oklahoma City, OK, USA: Ground Water Protection Council (GWPC). Available: http://fracfocus.org/chemical-use/what-chemicals-are-used [Accessed 18 March 2015].

FracFocus. **2015**. *Find a well* [Online] Oklahoma City, OK, USA: Ground Water Protection Council (GWPC). Available: http://www.fracfocusdata.org/DisclosureSearch/ [Accessed 8 March 2015].

Freyman, M. and Salmon, R. **2013**. *Hydraulic fracturing and water stress: Growing competitive pressures for water*. *Ceres*. Boston, MA, USA. Retrieved from: http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers.

FT. **2016**. *Commodities* [Online] London, UK: Financial Times (FT). Available: http://markets.ft.com/research/markets/Commodities [Accessed February 2017].

Fullenbaum, R. F., Larson, J. W. and Dorsey, J. **2011**. *The economic and employment contributions of shale gas in the United States*. *IHS Global Insight (USA)*. Washington DC. Retrieved from: http://anga.us/media/content/F7D1750E-9C1E-E786-674372E5D5E98A40/files/shale-gas-economic-impact-dec-2011.pdf.

Gall, C. **2015**. Algeria: violence erupts at protests over shale gas drilling project. *The New York Times*, March 1, 2015, Available from: http://www.nytimes.com/2015/03/02/world/africa/algeria-violence-erupts-at-protest-over-shale-gas-drilling-project.html.

Gamper-Rabindran, S. **2014**. Information collection, access, and dissemination to support evidence-based shale gas policies. *Energy Technology*, 2, 977-987.

Garcia, A. D. **2014**. One dead, two injured in Weld fracking incident. *The Coloradoan*, November 14, 2014, Available from: http://www.coloradoan.com/story/news/local/windsor/2014/11/13/one-killed-two-injured-weld-fracking-site/18981811/.

Gilbert, D. **2012**. Chemical makers ride gas boom. *The Wall Street Journal*, April 18, 2015, Available from: http://www.wsj.com/articles/SB10001424052702304331204577352161288275978.

Goodwin, S., Carlson, K., Knox, K., Douglas, C. and Rein, L. **2014**. Water intensity assessment of shale gas resources in the Wattenberg Field in Northeastern Colorado. *Environmental Science and Technology*, 48, 5991-5995.

Gordalla, B., Ewers, U. and Frimmel, F. **2013**. Hydraulic fracturing: a toxicological threat for groundwater and drinking-water? *Environmental Earth Sciences*, 70, 3875-3893.

Government of Alberta. **2014**. *Shale gas* [Online] Edmonton, AB, CAN: Government of Alberta. Available: http://www.energy.alberta.ca/NaturalGas/944.asp [Accessed December 2014].

Graham, J., Irving, J., Tang, X., Sellers, S., Crisp, J., Horwitz, D., Muehlenbachs, L., Krupnick, A. and Carey, D. **2015**. Increased traffic accident rates associated with shale gas drilling in Pennsylvania. *Accident Analysis and Prevention*, 74, 203-209.

Grant, L. and Chisholm, A. **2014**. *Shale gas and water: An independent review of shale gas exploration and exploitation in the UK with a particular focus on the implications for the water environment*. September, 2014. *Chartered Institute of Water and Environmental Management (CIWEM)*. London, UK. Retrieved from: http://www.ciwem.org/policy-and-international/current-topics/energy.aspx.

Gribben, R. **2014**. Ineos clinches shale contracts. *The Telegraph*, 17 February, 2015, Available from: http://www.telegraph.co.uk/finance/newsbysector/energy/oilandgas/10644781/Ineos-clinches-shale-contracts.html.

Hitzman, M. W., Emmanuel Detournay, Clarke, D. D., Dieterich, J. H., Dillon, D. K., Green, S. J., Habiger, R. M., McGuire, R. K., Mitchell, J. K., Shemeta, J. E. and Smith, J. L. **2012**. *Induced seismicity potential in energy technologies*. October, 2014. *National Research Council of the National Academies*. Washington DC. Retrieved from: http://www.nap.edu/catalog/13355/induced-seismicity-potential-in-energy-technologies.

HM Government. **2015**. *Infrastructure Act 2015, Chapter 7*, The Stationery Office (TSO), London, UK.

HM Treasury. **2014**. *Autumn statement 2014*, The Crown, London, UK.

House of Lords. **2013**. *No country is an energy island: securing investment for the EU's future*. *The European Union Committee*. London, UK. Retrieved from: http://www.parliament.uk/documents/lords-committees/eu-sub-com-d/energy/euenergypolicyfinalreport.pdf.

House of Lords. **2014**. *The economic impact on UK energy policy of shale gas and oil*. May, 2014. *House of Lords: Economic Affairs Committee*. London, UK. Retrieved from: http://www.publications.parliament.uk/pa/ld201314/ldselect/ldeconaf/172/172.pdf.

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

HSE. **2013**. *Control of exposure to silica dust* [Online] London, UK: Health and Safety Executive (HSE). Available: www.hse.gov.uk/pubns/indg463.htm [Accessed 5 May 2015].

HSE. **2015**. *Statistics: Industries* [Online] London, UK: Health and Safety Executive (HSE). Available: http://www.hse.gov.uk/Statistics/industry/index.htm [Accessed August 2015].

Huda, S. **2014**. Feasibility of KSA's shale gas project. *Arab News*, February 21, 2014, Available from: http://www.arabnews.com/news/528631.

Hultman, N., Rebois, D., Scholten, M. and Ramig, C. **2011**. The greenhouse impact of unconventional gas for electricity generation. *Environmental Research Letters*, 6, 044008.

IEA. **2011**. *World energy outlook 2011: Are we entering a golden age of gas?* . *International Energy Agency (IEA)*. Paris, FR. Retrieved from: http://www.worldenergyoutlook.org/media/weowebsite/2011/weo2011_goldenageofgasreport.pdf.

IEA. **2014a**. *2014 key world energy statistics*. *International Energy Agency (IEA)*. Paris, FR. Retrieved from: http://www.iea.org/newsroomandevents/agencyannouncements/key-world-energy-statistics-2014-now-available-for-free.html.

IEA. **2014b**. *Countries* [Online] Paris, FR: International Energy Agency (IEA). Available: https://www.iea.org/countries/ [Accessed April 2017].

Jackson, R. B., Vengosh, A., Carey, J. W., Davies, R. J., Darrah, T. H., O'Sullivan, F. and Petron, G. **2014**. The environmental costs and benefits of fracking. *Annual Review of Environment and Resources*, 39, 327-362.

Jackson, R. B., Vengosh, A., Darrah, T. H., Warner, N. R., Down, A., Poreda, R. J., Osborn, S. G., Zhao, K. and Karr, J. D. **2013**. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. *Proceedings of the National Academy of Sciences*, 110, 11250-11255.

Jacquet, J. B. **2014**. Review of risks to communities from shale energy development. *Environmental Science and Technology*, 48, 8321-8333.

Jaspal, R., Nerlich, B. and Lemancyzk, S. **2014**. Fracking in the Polish press: Geopolitics and national identity. *Energy Policy*, 74, 253-261.

Jeong, S., Millstein, D. and Fischer, M. L. **2014**. Spatially explicit methane emissions from petroleum production and the natural gas system in California. *Environmental Science and Technology*, 48, 5982-5990.

Jiang, M., Griffin, W. M., Hendrickson, C., Jaramillo, P., VanBriesen, J. and Venkatesh, A. **2011**. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environmental Research Letters*, 6, 034014.

Jiang, M., Hendrickson, C. T. and VanBriesen, J. M. **2014**. Life cycle water consumption and wastewater generation impacts of a Marcellus shale gas well. *Environmental Science and Technology*, 48, 1911-1920.

Johri, M. and Zoback, M. D. **2013**. *The evolution of stimulated reservoir volume during hydraulic stimulation of shale gas formations (Conference)*. Unconventional Resources Technology Conference. 12-14 August 2013 Denver, CO, USA.

Jupia Consultants Inc. **2014**. *Potential New Brunswick energy infrastructure and natural resource investment review (2015-2020)*. April, 2014. *Province of New Brunswick*. Moncton, CAN. Retrieved from: http://strongernb.ca/pdf/OurPathToAStrongerNewBrunswick.pdf.

Karion, A., Sweeney, C., Petron, G., Frost, G., Michael Hardesty, R., 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. and Conley, S. **2013**. Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophysical Research Letters*, 40, 4393-4397.

Kohl, C. A. K., Rosemary C.Capo, Brian W. Stewart, Andrew J. Wall, Karl T. Schroeder, Richard W. Hammack and George D. Guthrie **2014**. Strontium isotopes test long-term zonal isolation of injected and Marcellus formation water after hydraulic fracturing. *Environmental Science and Technology*, 48, 9867-9873.

Koppelmann, B., Walker, A. and Woods., E. **2012**. *Shale gas extraction in the UK: A review of hydraulic fracturing*. *The Royal Academy of Engineering*. London, UK. Retrieved from: https://royalsociety.org/~/media/policy/projects/shale-gas-extraction/2012-06-28-shale-gas.pdf.

Kuuskraa, V. A., Stephens, S. H. and Moodhre, K. D. **2013**. *Technically recoverable shale oil and shale gas resources: An assessment of 137 shale formations in 41 countries outside the United States*. *U.S. Energy Information Administration (EIA)*. Washington DC. Retrieved from: https://www.eia.gov/analysis/studies/worldshalegas/.

Lauletta, K. **2014**. Sasol picks Fluor for Louisiana ethane cracker complex. *Oilonline*, October 28, 2014, Available from: https://www.oilonline.com/news/downstream/sasol-picks-flour-louisiana-ethane-cracker-complex.

Laurenzi, I. J. and Jersey, G. R. **2013**. Life cycle greenhouse gas emissions and freshwater consumption of Marcellus shale gas. *Environmental Science and Technology*, 47, 4896-4903.

Levi, M. **2013**. Climate consequences of natural gas as a bridge fuel. *Climatic Change*, 118, 609-623.

Lewis, C., Speirs, J. and MacSweeney, R. **2014**. *Getting ready for UK shale gas: Supply chain and skills requirements and opportunities*. *United Kingdon Onshore Oil and Gas and Ernst and Young*. London, UK. Retrieved from: http://www.ey.com/Publication/vwLUAssets/Getting_ready_for_UK_shale_gas/$FILE/EY-Getting-ready-for-UK-shale-gas-April-2014.pdf.

Lewis, D. and Taylor, C. **2012**. *Britain's shale gas potential*. October, 2013. *Institute of Directors (IoD)*. London, UK. Retrieved from: www.iod.com/~/media/Documents/.../IoD_Britains_shale_gas_potential.

Lisak, J. **2015**. List of the harmed. *Pennsylvannia Alliance for Clean Water and Air* [Online].Web log post. Available from: http://pennsylvaniaallianceforcleanwaterandair.wordpress.com/the-list/ [Accessed: 21 July 2015].

Lyon, D. and Chu, T. **2011**. *Emissions inventory and ambient air monitoring of natural gas production in the Fayetteville Shale region*. November, 2013. *Arkansas Department of Environmental Quality (ADEQ)*. North Little Rock, AR, USA. Retrieved from: www.epa.gov/ttnchie1/conference/ei20/session6/dlyon.pdf.

Macey, G., Breech, R., Chernaik, M., Cox, C., Larson, D., Thomas, D. and Carpenter, D. **2014**. Air concentrations of volatile compounds near oil and gas production: a community-based exploratory study. *Environmental Health*, 13:82, 1-18.

Mackay, D. J. C. and Stone., T. J. **2013**. *Potential greenhouse gas emissions associated with shale gas extraction and use*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/237330/MacKay_Stone_shale_study_report_09092013.pdf.

Malik, N. **2015**. Haynesville shale gas costs cuts lure drillers from Marcellus *Bloomberg Business*, March 11, 2015, Available from: http://www.bloomberg.com/news/articles/2015-03-11/haynesville-shale-gas-cost-cuts-lure-drillers-from-marcellus.

Manda, A. K., Heath, J. L., Klein, W. A., Griffin, M. T. and Montz, B. E. **2014**. Evolution of multi-well pad development and influence of well pads on environmental violations and wastewater volumes in the Marcellus shale (USA). *Journal of Environmental Management*, 142, 36-45.

Mauter, M. S., Alvarez, P. J. J., Burton, A., Cafaro, D. C., Chen, W., Gregory, K. B., Jiang, G., Li, Q., Pittock, J., Reible, D. and Schnoor, J. L. **2014**. Regional variation in water-related impacts of shale gas development and implications for emerging international plays. *Environmental Science and Technology*, 48, 8299-8306.

McGlade, C., Bradshaw, M., Anandarajah, G., Watson, J. and Ekins., P. **2014**. *A bridge to a low-carbon future? Modelling the long-term global potential of natural gas - Research report*. November, 2014. *UK Energy Research Council (UKERC)*. London, UK. Retrieved from: http://www.ukerc.ac.uk/publications/gas-as-a-bridge.html.

McGrath, K. and Marinelli, M. **2012**. *Female workforce participation in the Australian oil and gas industry- a global comparison (Conference)*. 2012 APPEA National Oil and Gas Conference. 2012 Perth, AU.

McHugh, T., Molofsky, L., Daus, A. and Connor, J. **2014**. Comment on "An evaluation of water quality in private drinking water wells near natural gas extraction sites in the Barnett Shale formation". *Environmental Science and Technology*, 48, 3595-3596.

MDH. **2015**. *Volatile organic compounds in your home* [Online] St. Paul, MN, USA: Minnesota Department of Health (MDH). Available: http://www.health.state.mn.us/divs/eh/indoorair/voc/ [Accessed August 2015].

Mekonnen, M. M., Gerbens-Leenes, P. W. and Hoekstra, A. Y. **2015**. The consumptive water footprint of electricity and heat: a global assessment. *Environmental Science: Water Research and Technology*, 1, 285-297.

Mersich, A. **2013**. *Potential economic impacts of developing Quebec's shale gas*. April, 2015. *Canadian Energy Research Institute*. Calgary, CAN. Retrieved from: http://www.ceri.ca/index.php?option=com_content&view=article&id=105:ceri-study-132-potential-economic-impacts-of-developing-quebecs-shale-gas&catid=36:publication-pages.

Molofsky, L. J., Connor, J. A. and Farhat, S. K. **2011**. Methane in Pennsylvania water wells unrelated to Marcellus shale fracturing. *Oil and Gas Journal*, May 12, 2014, Available from: http://www.ogj.com/1/vol-109/issue-49/exploration-development/methane-in-pennsylvania-water-full.html.

Moniz, E. J., Jacoby, H. d., Meggs, A. J. M., Armstrong, R. C., cohn, D. R., Connors, S. R., Deutch, J. M., Ejaz, Q. J., Hezir, J. S., Kaufman, G. M., Kenderdine, M. a., O'Sullivan, F., Paltsev, S., Parsons, J. E., Perez-Arriaga, I., Reilly, J. M., Seto, C., Webster, M. D., Yang, Y., McRae, G. S. and Ruppel, C. **2011**. *The future of natural gas: an interdisciplinary MIT study*. *Massachusetts Institute of Technology Energy Initiative (MITEI)*. Cambridge, MA, USA. Retrieved from: https://mitei.mit.edu/system/files/NaturalGas_Report.pdf.

Moore, V., Bereford, A., Gove, B., Underhill, R., Parnham, S., Crow, H., Cunningham, R., Huyton, H., Sutton, J., Melling, T., Billings, P. and Salter, M. **2014**. *Hydraulic fracturing for shale gas in the UK: Examining the evidence for potential environmental impacts*. *The Royal Society for the Protection of Birds (RSPB)*. London, UK. Retrieved from: https://www.rspb.org.uk/Images/shale_gas_report_evidence_tcm9-365779.pdf.

Moors, K. **2014**. Is geothermal power about to become the next great battleground over fracking? *Oil and Energy Investor*, September 12, 2014, Available from: http://oilandenergyinvestor.com/2014/09/geothermal-power-become-next-great-battleground-fracking/.

Moylan, J. **2014**. Ineos to invest £640m in UK shale gas exploration. *BBC News*, November 20, 2014, Available from: http://www.bbc.co.uk/news/business-30125028.

Muehlenbachs, L. A., Spiller, E. B. and Timmins, C. **2013**. *Shale gas development and the cost of groundwater contamination risk*. February, 2014. *Resources for the Future*. Washington DC. Retrieved from: http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-DP-12-40-REV.pdf.

Mulloy, K. B. **2014**. Occupational health and safety considerations in oil and gas extraction operations. *National Academy of Engineering (NAE)*, 44, 41-46.

Myers, E. and Poole, P. **2014**. OSHA seeks to limit silica exposure for oil worker, proposed rules target frac sand mining, fracturing. *Unconventional Oil and Gas Report (online)* [Online], 2. Available: http://www.ogj.com/articles/uogr/print/volume-2/issue-6/osha-seeks-to-limit-silica-exposure-for-oil-workers-proposed-rules-target-frac-sand-mining-fracturing.html [Accessed: November 2015].

Newell, R. G. and Raimi, D. **2014**. Implications of shale gas development for climate change. *Environmental Science and Technology*, 48, 8360-8368.

O'Hara, S., Humphrey, M., Andersson-Hudson, J. and Knight, W. **2015**. *Public perception of shale gas extraction in the UK: Two years on from the Balcombe protests*. *University of Nottingham*. Nottingham, UK. Retrieved from: http://bettersociety.net/images/Public%20Perceptions%20of%20shale%20gas%20in%20the%20UK%20sept131015MH.WK.JA-H.pdf.

Office of Fossil Energy. **2013**. *Summary of LNG export applications* [Online] Washington DC: US Department of Energy Office of Fossil Energy. Available: http://energy.gov/fe/downloads/summary-lng-export-applications-lower-48-states [Accessed November 2014].

OGP. **2013**. *Shaping safety culture through safety leadership*. April, 2014. *International Association of Oil and Gas Producers (OGP)*. London, UK. Retrieved from: http://www.ogp.org.uk/pubs/452.pdf.

Oil & Gas UK. **2011**. *2011 UKCS workforce demographics report*. January, 2015. *Oil and Gas UK*. London, UK. Retrieved from: http://www.oilandgasuk.co.uk/cmsfiles/modules/publications/pdfs/EM010.pdf.

Oil prices. **2015**. Unconventional but normal. *The Economist*, April 18, 2015, Available from: http://www.economist.com/news/finance-and-economics/21648622-fall-oil-price-has-not-curbed-fracking-nearly-much.

Olaguer, E. P. **2012**. The potential near-source ozone impacts of upstream oil and gas industry emissions. *Journal of the Air and Waste Management Association*, 62, 966-977.

ONS. **2014**. *Labour market statistics, June 2014*. June, 2014. *Office for national Statistics (ONS)*. London, UK. Retrieved from: http://www.ons.gov.uk/ons/rel/lms/labour-market-statistics/june-2014/statistical-bulletin.html.

Oram, B., Halsor, S. and Redmond, B. **2011**. *Pennsylvania drinking water quality- Your private well: What do the results mean?*, Second, Wilkes-Barre, PA, USA: Wilkes University.

Orem, W., Tatu, C., Varonka, M., Lerch, H., Bates, A., Engle, M., Crosby, L. and McIntosh, J. **2014**. Organic substances in produced and formation water from unconventional natural gas extraction in coal and shale. *International Journal of Coal Geology*, 126, 20-31.

Osborn, S. G., Vengosh, A., Warner, N. R. and Jackson, R. B. **2011**. Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings of the National Academy of Sciences*, 108, 8172-8176.

OSHA. **2014**. *Worker exposure to silica during hydraulic fracturing* [Online] Washington DC: Occupational Safety and Health Administration (OSHA). Available: https://www.osha.gov/dts/hazardalerts/hydraulic_frac_hazard_alert.html [Accessed December 2014].

Pacsi, A. P., Sanders, K. T., Webber, M. E. and Allen, D. T. **2014**. Spatial and temporal impacts on water consumption in Texas from shale gas development and use. *ACS Sustainable Chemistry and Engineering*, 2, 2028-2035.

Parker, K. M., Zeng, T., Harkness, J., Vengosh, A. and Mitch, W. A. **2014**. Enhanced formation of disinfection by-products in shale gas wastewater-Impacted drinking water supplies. *Environmental Science and Technology*, 48, 11161-11169.

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. and Tans, P. **2012**. Hydrocarbon emissions characterization in the Colorado Front Range: A pilot study. *Journal of Geophysical Research: Atmospheres*, 117, 1-19.

Pirzadeh, P., Lesage, K. L. and Marriott, R. A. **2014**. Hydraulic fracturing additives and the delayed onset of hydrogen sulfide in shale gas. *Energy and Fuels*, 28, 4993-5001.

PwC. **2011**. *Shale Gas: A renaissance in US manufacturing*. *PricewaterhouseCoopers (PWC)*. Washington DC. Retrieved from: http://www.pwc.com/us/en/industrial-products/publications/shale-gas.html.

PwC. **2012**. *Shale gas: Reshaping the US chemicals Industry*. *PricewaterhouseCoopers (PWC)*. Washington DC. Retrieved from: https://www.pwc.com/us/en/industrial-products/publications/assets/pwc-shale-gas-chemicals-industry-potential.pdf.

Rabinowitz, P. M., Slizovskiy, I. B., Vanessa Lamers, S. J. T., Holford, T. R., Dziura, J. D., Peduzzi, P. N., Kane, M. J., Reif, J. S., Weiss, T. R. and Stowe, M. H. **2014**. Proximity to natural gas wells and reported health status: Results of a household survey in Washington County, Pennsylvania. *Environmental Health Perspectives*, 123, 21-26.

Rahm, B. G. and Riha, S. J. **2012**. Toward strategic management of shale gas development: Regional, collective impacts on water resources. *Environmental Science and Policy*, 17, 12-23.

Rahm, B. G. and Riha, S. J. **2014**. Evolving shale gas management: water resource risks, impacts, and lessons learned. *Environ. Sci.: Processes Impacts*, 16, 1400-1412.

Rahm, D. **2011**. Regulating hydraulic fracturing in shale gas plays: The case of Texas. *Energy Policy*, 39, 2974-2981.

Raimi, K. T. and Leary, M. R. **2014**. Belief superiority in the environmental domain: Attitude extremity and reactions to fracking. *Journal of Environmental Psychology*, 40, 76-85.

Regeneris Consulting. **2011**. *Economic impact of shale gas exploration and production in Lancashire and the UK*. October, 2014. *Cuadrilla Resources Ltd*. Altringham, UK. Retrieved from: http://www.cuadrillaresources.nl/wp-content/uploads/2012/02/Full_Report_Economic_Impact_of_Shale_Gas_14_Sept.pdf.

RenewableUK. **2015**. *Standards and certification* [Online] London, UK: RenewableUK. Available: http://www.renewableuk.com/en/renewable-energy/wind-energy/small-and-medium-scale-wind/standards-and-certification.cfm [Accessed August 2015].

Riedl, J., Rotter, S., Faetsch, S., Schmitt-Jansen, M. and Altenburger, R. **2013**. Proposal for applying a component-based mixture approach for ecotoxicological assessment of fracturing fluids. *Environmental Earth Sciences*, 70, 3907-3920.

RSPB. **2014**. *Are we fit to frack?* March, 2014. *The Royal Society for the Protection of Birds (RSPB)*. London, UK. Retrieved from: https://www.rspb.org.uk/Images/shale_gas_summary_tcm9-365778.pdf.

Rubinstein, J. L., Ellsworth, W. L., McGarr, A. and Benz, H. M. **2014**. The 2001 induced earthquake sequence in the Raton Basin of Northern New Mexico and Southern Colorado. *Bulletin of the Seismological Society of America*, 104, 2162-2181.

Scanlon, B. R., Reedy, R. C. and Nicot, J.-P. **2014**. Comparison of water use for hydraulic fracturing for shale oil and gas production versus conventional oil. *Environmental Science and Technology*, 48, 12386-12393.

Schafft, K. A., Glenna, L. L., Green, B. and Borlu, Y. **2014**. Local impacts of unconventional gas development within Pennsylvania's Marcellus Shale region: Gauging boomtown development through the perspectives of educational administrators. *Society and Natural Resources*, 27, 389-404.

Schmitt-Jansen, M., Riedl, J., Rotter, S. and Altenburger, R. **2012**. *Ecotoxicological assessment of chemicals used in fraccing fluids*. February, 2014. *Helmholtz-Centre for Environmental Research*. Leipzig, DE. Retrieved from: http://dialog-erdgasundfrac.de/ecotoxicological-assessment-chemicals-used-fraccing-fluids.

Schnoor, J. L. **2014**. Re-emergence of emerging contaminants. *Environmental Science and Technology*, 48, 11019-11020.

Shaffer, D. L., Arias Chavez, L. H., Ben-Sasson, M., Romero-Vargas Castrillon, S., Yip, N. Y. and Elimelech, M. **2013**. Desalination and reuse of high-salinity shale gas produced water: Drivers, technologies, and future directions. *Environmental Science and Technology*, 47, 9569-9583.

Singh, R. D. **2004**. *Principles and practices of modern coal mining*, First New Delhi, IN: New Age International.

Skone, T. J., Littlefield, J. and Marriot, J. **2011**. *Life cycle greenhouse gas inventory of natural gas extraction, delivery and electricity production*. *National Energy Technology Laboratory*. Morgantown, WV, USA. Retrieved from: http://www.netl.doe.gov/energy-analyses/pubs/NG-GHG-LCI.pdf.

Slonecker, E. T., Milheim, L. E., Roig-Silva, C. M., Malizia, A. R., Marr, D. A. and Fisher, G. B. **2012**. *Landscape consequences of natural gas extraction in Bradford and Washington Counties, Pennsylvania, 2004 - 2010*. January, 2014. *The Geological Society of America*. Boulder, CO, USA. Retrieved from: pubs.usgs.gov/of/2012/1154/of2012-1154.pdf.

Soeder, D. J., Sharma, S., Pekney, N., Hopkinson, L., Dilmore, R., Kutchko, B., Stewart, B., Carter, K., Hakala, A. and Capo, R. **2014**. An approach for assessing engineering risk from shale gas wells in the United States. *International Journal of Coal Geology*, 126, 4-19.

Solar Trade Association. **2015**. *What is a solar farm?* [Online] London, UK: Solar Trade Association. Available: http://www.solar-trade.org.uk/solar-farms/ [Accessed August 2015].

Sommariva, R., Blake, R. S., Cuss, R. J., Cordell, R. L., Harrington, J. F., White, I. R. and Monks, P. S. **2014**. Observations of the release of non-methane hydrocarbons from fractured shale. *Environmental Science and Technology*, 48, 8891-8896.

Sovacool, B. K. **2014**. Cornucopia or curse? Reviewing the costs and benefits of shale gas hydraulic fracturing (fracking). *Renewable and Sustainable Energy Reviews*, 37, 249 - 264.

Stamford, L. and Azapagic, A. **2014**. Life cycle environmental impacts of UK shale gas. *Applied Energy*, 134, 506 - 518.

Stanek, W. and Bialecki, R. **2014**. Can natural gas warm the climate more than coal? *Fuel*, 136, 341-348.

State of Louisiana Department of Natural Resources. **2011**. *Comparison of state hydraulic fracturing chemical disclosure regulations* [Online] Baton Rouge, LA, USA: State of Louisiana Department of Natural Resources. Available: http://dnr.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&pid=888 [Accessed December 2013].

Steinzor, N., Subra, W. and Sumi, L. **2013**. Investigating link between gas development and health impacts through a community survey project in Pennsylvania. *New Solutions*, 23, 55-83.

Stephenson, T., Valle, J. E. and Riera-Palou, X. **2011**. Modeling the Relative GHG Emissions of Conventional and Shale Gas Production. *Environmental Science and Technology*, 45, 10757-10764.

Stoker, T. F., Qin, D., Plattner, G.-K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P. M. **2013**. *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change*. *The Intergovernmental Panel on Climate Change (IPCC)*. Cambridge, UK. Retrieved from: www.ipcc.ch/report/ar5/wg1/.

Sullivan, D. **2014**. *Eagle Ford Shale mobile monitoring study*. November, 2013. *The University of Texas at Austin*. Austin, TX, USA. Retrieved from: https://www.tceq.texas.gov/airquality/eagleford/eagle-ford-main.

Tarver, N. **2013**. Fracking protest 'scars' Balcombe village. *BBC News*, December 28, 2013, Available from: http://www.bbc.co.uk/news/uk-england-sussex-25340896.

Taylor, C. and Lewis, D. **2013**. *Getting shale gas working*. *Institute of Directors (IoD)*. London, UK. Retrieved from: www.iod.com/~/media/.../IoD_Getting_shale_gas_working_MAIN_REPORT.pdf.

Teasdale, C. J., Hall, J. A., Martin, J. P. and Manning, D. A. C. **2014**. Ground gas monitoring: Implications for hydraulic fracturing and CO2 storage. *Environmental Science and Technology*, 48, 13610-13616.

Thurman, E. M., Ferrer, I., Blotevogel, J. and Borch, T. **2014**. Analysis of hydraulic fracturing flowback and produced waters using accurate mass: Identification of ethoxylated surfactants. *Analytical Chemistry*, 86, 9653-9661.

Tian, L., Wang, Z., Krupnick, A. and Liu, X. **2014**. Stimulating shale gas development in China: A comparison with the US experience. *Energy Policy*, 75, 109-116.

U.S. Census Bureau. **2012**. *Statistical abstract of the United States: 2012 (131st Edition)*. February, 2015. *U.S. Census Bureau*. Washington DC. Retrieved from: http://www.census.gov/compendia/statab/.

UNEP. **2012**. *The need for numbers - goals, targets and indicators for the environment* [Online] Nairobi, KEN: United Nations Environment Program (UNEP). Available: http://www.unep.org/pdf/GEAS_Mar2012_Indicator.pdf [Accessed March 2015].

United States Department of Labor. **2015**. *Safety and health topics: Hydrogen sulfide* [Online] Washington DC: United States Department of Labor. Available: https://www.osha.gov/SLTC/hydrogensulfide/hazards.html [Accessed August 2015].

Uth, H.-J. **2014**. Technical risks and best available technology (BAT) of hydraulic fracturing in unconventional natural gas resources. *Environmental Earth Sciences*, 72, 2163-2171.

van der Voort, N. and Vanclay, F. **2015**. Social impacts of earthquakes caused by gas extraction in the Province of Groningen, The Netherlands. *Environmental Impact Assessment Review*, 50, 1-15.

Vengosh, A., Jackson, R. B., Warner, N., Darrah, T. H. and Kondash, A. **2014**. A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. *Environmental Science and Technology*, 8334-8348.

Vengosh, A., Warner, N., Jackson, R. and Darrah, T. **2013**. The effects of shale gas exploration and hydraulic fracturing on the quality of water resources in the United States. *Procedia Earth and Planetary Science*, 7, 863-866.

Vikram, A., Lipus, D. and Bibby, K. **2014**. Produced water exposure alters bacterial response to biocides. *Environmental Science and Technology*, 48, 13001-13009.

Wang, Q., Chen, X., Jha, A. N. and Rogers., H. **2014**. Natural gas from shale formation - The evolution, evidences and challenges of shale gas revolution in United States. *Renewable and Sustainable Energy Reviews*, 30, 1-28.

Wang, Z. and Krupnick, A. **2013a**. *A retrospective review of shale gas development in the United States*. February, 2014. *Resources for the Future*. Washington DC. Retrieved from: www.rff.org/RFF/documents/RFF-DP-13-12.pdf.

Wang, Z. and Krupnick, A. **2013b**. *US shale gas development: What led to the boom?* January, 2014. *Resources for the Future*. Washington DC. Retrieved from: www.rff.org/RFF/Documents/RFF-IB-13-04.pdf.

Warner, N. R., Darrah, T. H., Jackson, R. B., Millot, R., Kloppmann, W. and Vengosh, A. **2014**. New tracers identify hydraulic fracturing fluids and accidental releases from oil and gas operations. *Environmental Science and Technology*, 48, 12552-12560.

Warner, N. R., Jackson, R. B., Darrah, T. H., Osborn, S. G., Down, A., Zhao, K., White, A. and Vengosh, A. **2012**. Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. *Proceedings of the National Academy of Sciences*, 109, 11961-11966.

Webber, M. E. **2012**. Natural gas's bright future in the United States. *Earth Magazine*, December 9, 2014, Available from: http://www.earthmagazine.org/article/highlights-2012-outlook-natural-gas.

Weber, C. L. and Clavin, C. **2012**. Life cycle carbon footprint of shale gas: Review of evidence and implications. *Environmental Science and Technology*, 46, 5688-5695.

Weijermars, R. **2013**. Economic appraisal of shale gas plays in Continental Europe. *Applied Energy*, 106, 100-115.

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

Woynillowicz, D. **2007**. Tar sands fever! *World Watch Magazine*, September, Available from: http://www.worldwatch.org/node/5287.

Yunna, W., Kaifeng, C., Yisheng, Y. and Tiantian, F. **2015**. A system dynamics analysis of technology, cost and policy that affect the market competition of shale gas in China. *Renewable and Sustainable Energy Reviews*, 45 235-243.

Yunna, W. and Yisheng, Y. **2014**. The competition situation analysis of shale gas industry in China: Applying Porter's five forces and scenario model. *Renewable and Sustainable Energy Reviews*, 40, 798-805.

Zavala-Araiza, D., Sullivan, D. W. and Allen, D. T. **2014**. Atmospheric hydrocarbon emissions and concentrations in the Barnett Shale natural gas production region. *Environmental Science and Technology*, 48, 5314-5321.

Chapter 3. Environmental impacts of shale gas in the UK: Current situation and future scenarios

This paper was published in the journal *Energy Technology* in November 2014 with the following citation:

> *Cooper, J., Stamford, L. and Azapagic, A. (2014), Environmental Impacts of Shale Gas in the UK: Current Situation and Future Scenarios. Energy Technology, 2: 1012–1026.*
> *http://dx.doi.org/10.1002/ente.201402097*

This paper presents the life cycle assessment of shale gas extracted in the UK and used to generate electricity, as well as the impact of shale gas electricity on the UK electricity mix. The introduction, tables and figures have been amended to fit into the structure of this thesis. An additional comparison to the results of the life cycle assessment by the supervisors of this PhD project (separate study and is discussed in Chapter 2) has been added to this chapter, as well as an additional sensitivity analysis (impacts of land use change on greenhouse gas emissions), both of which are not part of the published manuscript. The thesis author is the main author of the paper and collected the life cycle inventory data needed to model a shale gas well. The LCA models were built in GaBi by the author. The thesis author wrote the original manuscript to which the co-authors (the supervisors of this PhD project) contributed by reviewing the manuscript and the results of the GaBi models.

Environmental impacts of shale gas in the UK: Current situation and future scenarios

Jasmin Cooper, Laurence Stamford and Adisa Azapagic*

School of Chemical Engineering and Analytical Science, The University of Manchester, Manchester M13 9PL

*Corresponding author:

Tel: +044 (0) 161 306 4363; Fax: +044 (0) 161 306 9321

Email: adisa.azapagic@manchester.ac.uk

Abstract

The life cycle environmental impacts of UK shale gas used for electricity generation, in comparison with other fossil, nuclear and renewable options are presented. Per kWh of electricity generated, shale gas has higher environmental impacts than the other options, except for coal. Thus, if it were to replace coal, most impacts would be reduced, including the global warming potential (GWP; by 2.3-times). However, if it were to compete with nuclear power or some renewables most impacts would rise, with the GWP increasing by 5-123 times. Within a future UK electricity mix up to 2030, shale gas would make little difference to the environmental impacts of electricity generation, including the GWP, even for the most optimistic assumptions for its domestic production. This suggests that, in the medium term, shale gas cannot help towards meeting UK climate change targets and that certain renewables and nuclear power should be prioritised instead.

Keywords: climate change; electricity; environmental impacts; life cycle assessment; shale gas

1. Introduction

To broaden the understanding of the environmental consequences of shale gas, this study considers multiple environmental impacts of extracting shale gas in the UK and utilising it to generate electricity. Taking a life cycle approach, the impacts are estimated from 'cradle to grave' and compared to other electricity sources such as conventional gas, coal, nuclear and renewables. The role that shale gas could play in the future and how it could affect the environmental impacts and sustainability of electricity generation in the UK are also considered.

2. Methodology

Life cycle assessment (LCA) has been used to estimate environmental impacts, following the ISO 14040/44 methodology (ISO, 2006a; ISO, 2006b). LCA modelling has been carried out using the GaBi v.6 software package (PE, 2012). The goal of the study, data and the assumptions are defined below.

2.1. Goal and scope definition

The goal of the study is to estimate the life cycle environmental impacts of electricity generated from shale gas produced in the UK and compare it with the electricity options that make up the current electricity mix: conventional gas and LNG, coal, nuclear power, wind, solar photovoltaic (PV) and hydroelectricity. A further goal is to establish what effect shale gas electricity generation may have on the impacts of the UK electricity mix if used as part of the mix.

The functional unit is defined as the "*generation of 1 kWh of electricity"*. The scope of the study is from 'cradle to grave' for all the electricity options considered (Figure 13). Specifically, the life cycle of shale gas electricity involves the following stages:

- exploration and site preparation;
- well drilling and hydraulic fracturing;
- well completion and gas production;
- shale gas processing, distribution and electricity generation in a power plant (including plant construction and end-of-life decommissioning);
- waste disposal; and
- well closure.

These stages are described in turn next. This is followed by an overview of the other electricity options that contribute to the current UK electricity mix and a definition of future electricity scenarios, to determine what effect the use of shale gas may have on the impacts. Note that, as the functional unit relates to the generation rather than the consumption of electricity, its distribution and end-use are considered outside the system boundary.

2.2. The life cycle of electricity from shale gas

Exploration and site preparation: This is the initial stage in which the area of interest is prepared for drilling activities. Typically, this involves land clearing and road construction to enable access to the site.

Well drilling and hydraulic fracturing: A well is created by drilling down to a depth of approximately 1,500 m before deviating at an angle to form a horizontal section at least 1,500 m long (Clark et al., 2013) (Figure 14). A drilling fluid is used to aid the creation of the well and help carry the rock excavated by the drilling up to the surface. Many types of drilling fluid are used, but water-based fluids mixed with clay and chemicals such as barite are most common (Caenn et al., 2011). After drilling, the well is lined with steel casing to protect the surrounding rock and to improve the well's integrity. The top section of the well has three layers of steel casing to protect surface and ground water and the horizontal section is lined with a single layer of steel casing (Figure 14; A more detailed diagram can be found in Appendix A, Figure A2). After the well has been encased, the horizontal section of the well is perforated, typically using charges, to puncture holes in the casing (Clark et al., 2013). The well can then be fractured hydraulically.

Hydraulic fracturing, colloquially referred to as *fracking*, is the pumping of high-pressure fluid into the well to create fractures in the shale rock. The fracking fluid used is typically a mixture of water, proppant (sand) and chemical enhancers (Clark et al., 2013; Cuadrilla Resources, 2017). The water pushes its way through the casing perforations to the shale, where it creates a complex network of fractures. The proppant keeps the fractures open after pumping has finished, allowing the gas to travel through them, from the shale to the gas well. The chemical enhancers improve the characterisation and performance of the fracking fluid, for instance, by increasing its stability and reducing friction.

Well completion and gas production: After being fractured, the well is depressurised. The created pressure gradient allows the gas to flow from the rock into the well. However, before the gas can be extracted, the fracturing fluid needs to be removed. This is also done by depressurising, which pushes the fluid out of the well. The well is complete when the majority of liquid has been removed and gas flows freely and consistently.

Shale gas processing, distribution and electricity generation: The gas needs to be of a certain quality before it can be distributed and used for electricity generation. Impurities and heavy hydrocarbons are removed to produce a gas stream with a high methane concentration. The gas is then distributed through the gas network from the well site to the power plant to generate electricity.

Waste disposal and well closure: Waste from the well site consists primarily of waste fracturing fluid and drilling waste. The former is treated in a water treatment plant and the latter is incinerated, spread on land or landfilled. Finally, once the gas has been exhausted, the well is filled with cement and abandoned.

2.3. Life cycle of other electricity options

Electricity generation options that currently contribute to the UK mix include conventional gas, LNG, coal, nuclear power, wind, solar PV, hydroelectricity and biomass. Their respective life cycles from ‘cradle to grave’ are shown in Figure 13 (and figures A3 to A9 in Appendix A) and encompass the extraction and processing of raw materials and fuels, transport of fuels (where relevant), generation of electricity, construction and decommissioning of power plants and waste management throughout the life cycle.

It can be noted from Figure 13 that conventional gas has essentially the same life cycle as shale gas, except that only vertical drilling is required and hydraulic fracturing is not necessary, because of the high porosity of sandstone from which it is typically extracted (at 1,500-1,800 m below the surface) (EIA, 2014). Similar applies to LNG. The UK imports the vast majority of its LNG from Qatar, which is conventional gas that has been liquefied to allow it to be shipped over long distances, rather than being distributed by pipelines, as is the case with conventional gas. Liquefaction is carried out by cooling the gas to under -161°C at the place of export (Coffey Environments, 2011). The gas is then transported in special cryogenic ships and regasified at the point of import by gradually increasing the temperature to above 0°C under high pressure (Total S A, 2014). After regasification, the gas is distributed through pipelines to the power plant.

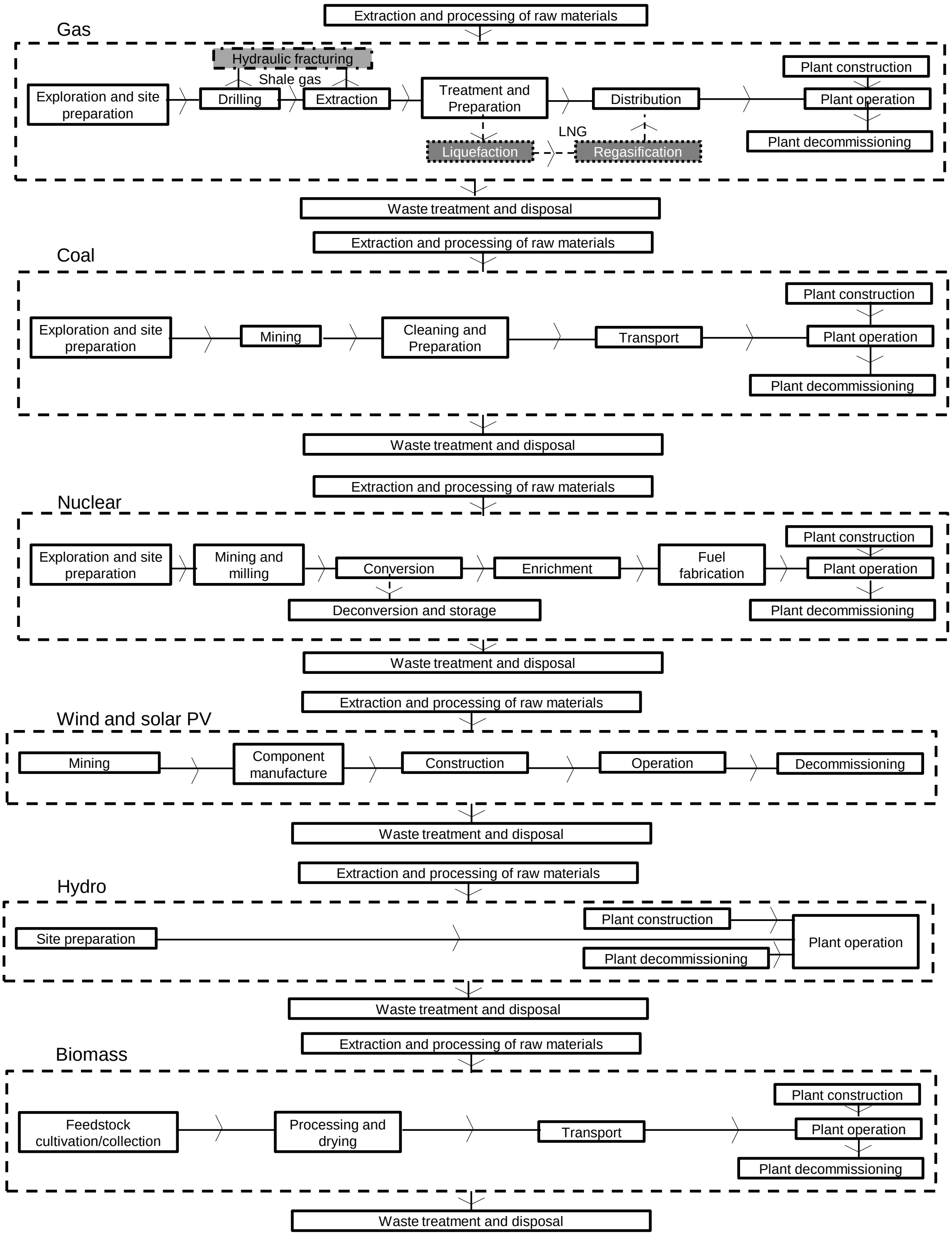


Figure 13: The life cycle of shale gas and other electricity options considered in the study (adapted from Stamford and Azapagic(Stamford and Azapagic, 2012)) "Gas" represents the life cycles of shale gas, conventional gas and LNG. The stage unique to shale gas is indicated by the light grey box, stages unique to LNG are shown in dark grey boxes and white boxes apply to all three options. For shale gas, in addition to vertical, horizontal drilling is also needed (not shown in the figure). Broken lines denote optional stages.

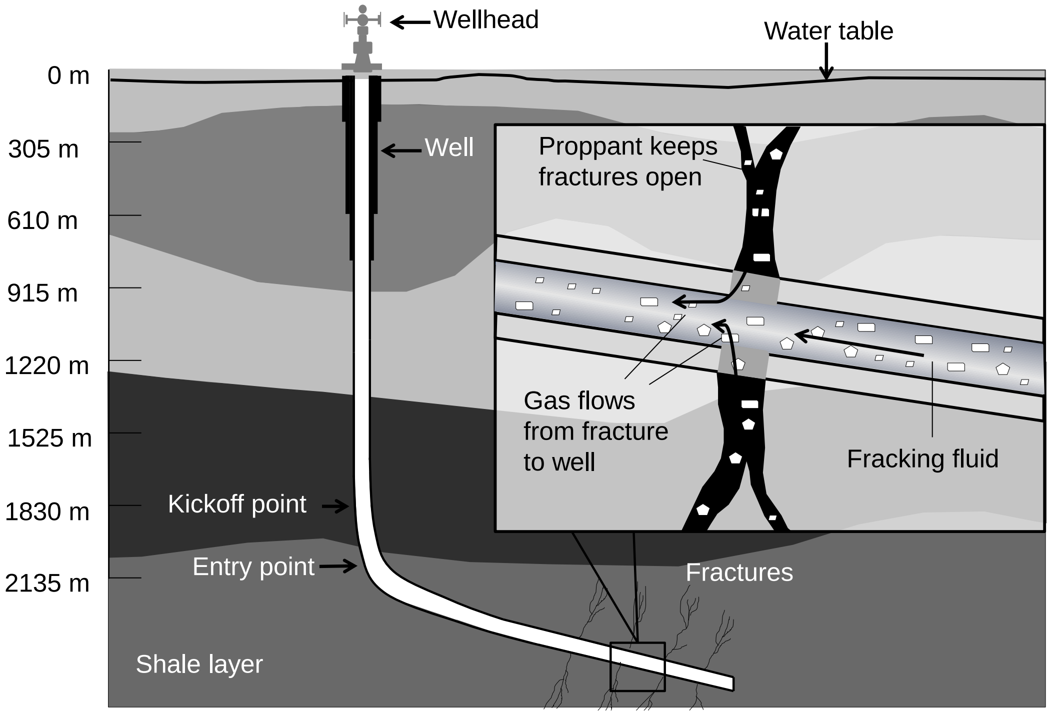


Figure 14: Typical shale gas well consisting of vertical and perforated horizontal sections. Inset: Injected fracking fluid fractures the rock to create a network through which the gas can travel to the well. Adapted from Figures 2 and 6 in chapters 1 and 2.

2.4. Inventory data and assumptions

2.4.1. Shale gas

As there is no commercial production of shale gas in the UK, in the absence of UK-specific data, the data for well preparation and the composition of shale gas are instead based on average USA data. However, wherever possible, these have been adapted to match UK conditions, as explained below. To determine the effect of data uncertainty on the results, three scenarios are considered: central, best and worst case. The central case represents an average-sized well that produces an average amount of gas. The best case relates to a small well that produces a large quantity of gas and the worst case represents a large well that produces a small amount of gas (Table 17 and tables B1 to B9 in Appendix B).

The data have been sourced from SONRIS (SONRIS, 2013) and FracFocus (FracFocus, 2014) (tables B1 to B9 in Appendix B). SONRIS is a public database for oil and gas activities in the Haynesville shale play in Louisiana, USA. This is the deepest of the major US shale plays and is the most similar in depth to the plays in the UK; therefore, it is likely that the well size and gas production statistics for Haynesville would be similar to UK shale gas wells (Clarke et al., 2014). The shale well data assumed are summarised in Table 17 for the central, best and worst cases based respectively on the average, minimum and maximum values, for the different parameters for 2386 wells in the Haynesville shale play.

The amount of drilling fluid has been calculated based on the American Petroleum Institute's (API) (API, 2000) data on the volume of drilling fluid used per volume of well. The ratio of 11 m^3 of water-based drilling fluid per m^3 volume of wellbore drilled has been assumed so that the total amount of drilling fluid is equal to 17,300 t (Table 17 and Table B10 in Appendix B). The assumed composition of the water-based drilling fluid is specified in Table 18. An oil-based fluid (Table B11 in Appendix B) is also considered in the sensitivity analysis later in the paper. The amount of drilling waste can be found in Table 17; for more details on the estimates of waste, see equations (B1) and (B2) and Table B10 in Appendix B.

The amount of fracturing fluid used in each Haynesville well has been sourced from Freyman and Salmon (2013) and FracFocus (FracFocus, 2014), the USA fracking fluid registry. Its composition is based on the data provided by Cuadrilla (Cuadrilla Resources, 2017), one of the main shale gas companies in the UK, with 99.95% being water and sand and 0.05% chemical enhancers (Table 20).

Table 17: Data for the shale gas well over the lifetime of the well[a] (API, 2000; Freyman and Salmon, 2013; FracFocus, 2014; SONRIS, 2013).

Factor	Central case (average)	Best case	Worst case
Steel (t)	513	162	823
Cement (t)	702	222	1,130
Drilling fluid (kt)	17.3	10.6	21.7
Hydraulic fracturing fluid (m^3)	23,200	318	40,700
Well length (m)	5,080	3,230	6,290
Estimated ultimate recovery (Mm^3)	122	1,260	10
Fugitive methane emissions (m^3)[b]	207,400	2,142,000	1,700
Drilling waste to landfill (kt)	12.9	7.8	16.4
Drilling waste spread on land (kt)	2.7	1.6	3.4
Drilling waste to incineration (kt)	2.3	1.4	3.0

[a] Based on shale gas production data for 2386 wells.
[b] Normal m^3 at standard conditions (1 bar and 15°C).

The assumed composition of shale gas is given in Table 19. As there are no UK-specific data, this is based on the average composition of shale gas in the USA (Table B12 in Appendix B) (George and Bowles., 2011). The amount of gas produced over the assumed 30-year lifetime of the well, known as the estimated ultimate recovery (EUR), has been calculated using a hyperbolic decline function (equation B3 in Appendix B) and the data from SONRIS for the initial (first month's) production of each of the 2386 gas wells considered. It was found that on average, the EUR is most typically in the range of 28-140 Mm^3 (Figure B1). However, the minimum EUR was found to be five to six orders of magnitude smaller than the maximum and average values as a result of extremely low initial production rates recorded in SONRIS. For this reason, a literature value for the minimum economic or breakeven EUR (Cohen, 2013) has been used instead, which corresponds to the maximum size of the well, denoted as the worst case in Table 17. Similarly and as mentioned previously, the maximum EUR corresponds to the gas recovery from the minimum well size in the best case and the average EUR relates to the average well in the central case.

The fugitive methane emissions during the well's operation have been estimated by assuming that 0.17% of total gas production (EUR) is lost in this way (Shires et al., 2009). The total amount of drilling waste has been estimated based on the data for solid and liquid waste generation as summarised in Table 17 and detailed in Table B10 in Appendix B. Greenhouse gas emissions from land use change are not considered in this work. This is because the UK currently does not have any active shale gas wells and potential future well sites are indefinite. However, the effect of land use change is considered in a sensitivity analysis.

It has been assumed that shale gas is used in a combined cycle gas turbine (CCGT) plant with an average efficiency of 53%, which is currently the case for electricity generated from natural gas in the UK (DECC, 2013b; DECC, 2013a). The background LCA data have been sourced from the Ecoinvent V2.2 database (Ecoinvent Centre, 2010) and adapted for UK conditions (see tables B13 and B14 in Appendix B).

Table 18: Composition of drilling fluid (Deville et al., 2011).

Component	**Composition (vol%)**
Water	29.3
Barite	66.5
Clay	1.36
Thinner (acetone)	0.68
Shale stabiliser (asphalt)	0.68
High temperature deflocculant (sodium carbonate)	0.54
Surfactant (sodium persulphate)	0.41
Fluid-loss-control polymer (methanol)	0.27
Buffer agent (acetic acid)	0.20
Caustic soda	0.07

Table 19: Composition of shale gas (George and Bowles., 2011).

Component	Composition[a] (vol%)
CH_4	86.8
C_2H_6	8.23
C_3H_8	1.65
C_4H_{10}	0.94
C_5H_{12}	0.11
CO_2	1.03
N_2	1.24

[a] At standard conditions (1 atm and 15°C).

Table 20: Materials used in hydraulic fracturing (Cuadrilla Resources, 2017; Freyman and Salmon, 2013).

Material	Amount per m^3 of fracturing fluid
Water (kg)	903
Sand (kg)	155
Polyacrylamide (g)	4.23
Sodium salt (mg)	5.29
Drilling electricity (diesel) (MJ)	44.7

2.4.2. Other electricity options and the current electricity mix

The current (2012) UK electricity mix is dominated by fossil fuels (68.7%), with low-carbon sources making up the remaining 31.3% (Table 21) (DECC, 2013c). Specifically:

- conventional natural gas supplies 24.2% of electricity, of which 46% is from the domestic supply in the North Sea and the rest is imported (Table 22);
- LNG supplies 4.3% of electricity and is largely imported from Qatar (98%; Table 22);
- coal is used to generate 39.4% of electricity, with most coal imported from Russia, Colombia and the USA;
- nuclear power contributes 18.5% using fuel sourced from Canada and Australia; and
- wind and solar PV supply 5.7 and 0.3%, respectively, with hydroelectricity providing 2.4% (including 0.9% of pumped storage) and biomass 4.4%.

Oil supplies only 0.8% of electricity and is being phased out so is not considered here.

The assumptions made for the current and future electricity options are as follows:

- conventional gas and LNG (CCGT): efficiency of 52.5%;
- coal (subcritical pulverised): 39.7% efficiency; 90% SO_2 capture by flue gas desulfurisation; 80% NO_x removal by selective catalytic reduction (Ecoinvent Centre, 2010; New Energy Externalities Development For Sustainability, 2010);
- coal with carbon capture and storage (CCS): oxy-fuel combustion; CO_2 injection into depleted gas fields and saline aquifers; efficiency of 37% (including losses from CCS);
- gas with carbon capture and storage: CCGT; CO_2 injection into depleted gas fields; efficiency of 53% (including losses from CCS);
- nuclear power (pressurised water reactor, PWR): 8% mixed oxide (MOX) fuel, 8% centrifuge enrichment and 92% diffusion enrichment;
- wind: 2.5 MW (onshore) and 4 MW (offshore) with 27.7% capacity factor;
- solar PV: 39% monocrystalline, 60% crystalline silicon and 1% thin film; 67% mounted on slanted roof, 17% on flat roof and 16% as building tiles;
- wave/tidal: 7 MW with 46% capacity factor; overtopping device such as "Wave Dragon";
- hydroelectricity: run-of-river and reservoirs with 82% electrical efficiency, pumped storage with 70% pump efficiency; and
- biomass: anaerobic digestion (94.9%), plant biomass (3.6%), animal biomass (2.4%) and landfill gas (0.2%); gas turbine with an efficiency of 34%.

End-of-life waste after plant decommissioning is assumed to be landfilled. The LCA data for the above options have been sourced from Ecoinvent and NEEDS (Ecoinvent Centre, 2010; New Energy Externalities Development For Sustainability, 2010) and adapted to UK conditions by altering all the electricity and gas inputs to match the UK 2012 mix.

Table 21: Current electricity mix and a future scenario up to 2030 (DECC, 2013c; DECC, 2013d).

Electricity source (type of plant)	**Current situation (2012)**		**Future scenario (2030)**	
	TWh	%	TWh	%
Coal (subcritical pulverised)	135.9	39.4	1.9	0.5
Oil (steam turbine)	2.7	0.8	3.6	0.9
Conventional gas (CCGT)[a]	83.5	24.2	59.1	15.3
LNG[b] (CCGT)	14.7	4.3	22.0	5.7
Shale gas (CCGT)	0	0	3.4	0.9
Coal and gas CCS[c] (post combustion)	0	0	33.3	8.7
Nuclear (PWR)[d]	63.9	18.5	101.8	26.4
Wind (offshore)	7.5	2.2	59.0	15.3
Wind (onshore)	12.1	3.5	45.7	11.9
Solar PV (crystalline silicon and thin film)	1.2	0.3	3.0	0.8
Wave/tidal	0	0	5.3	1.4
Hydro (run-of-river and reservoir)	5.3	1.5	8.5	2.2
Hydro (pumped storage)	3.0	0.9	3.5	0.9
Biomass[e] (gas turbine)	15.2	4.4	35.0	9.7
Total	345.0	100.0	385.1	100.0

[a] CCGT: combined cycle gas turbine.
[b] LNG: liquefied natural gas.
[c]: CCS: carbon capture and storage; post combustion CO_2 capture.
[d] PWR: pressurised water reactor.
[e] Anaerobic digestion (94.9%); plant biomass (3.6%); animal biomass (2.4%); landfill gas (0.2%).

2.4.3. Future gas and electricity mix

As mentioned in the goal and scope definition section, a future UK electricity mix is also considered to explore the role shale gas could play in supplying electricity, as well as its related contribution to environmental impacts. For these purposes, two electricity generation scenarios have been developed for the year 2030 based on projections by the UK Government (DECC, 2013d); these projections are specified in Table 21. The electricity scenarios are based on two equivalent scenarios for future sources of gas in the UK up to 2030: one based on projections by the Office of Gas and Electricity Markets (Ofgem) (Williams et al., 2011) and another developed as part of this work. Ofgem's assumptions for the extraction of shale gas in 2030 are conservative and its contribution to the overall gas mix is presumed small (4.5%; Table 22). The second scenario considers a situation in which shale gas extraction is more successful: in this case, the volumes of LNG and shale gas are swapped so that 28.4% comes from shale gas and 4.5% from LNG. The rationale for this is that domestic shale gas would be used preferentially over (more expensive) LNG imports. The rest of the mix is the same as that in Ofgem's scenario. These two gas mix scenarios have been incorporated into the corresponding low shale and high shale electricity scenarios, respectively, to consider the effect of different levels of shale gas penetration on the overall impacts of the electricity mix. As for the current situation, the LCA data for the electricity options in the scenarios have been sourced from Ecoinvent, making the same UK-specific adaptations as explained earlier. Future changes in technology efficiencies are not considered because of a lack of data.

Table 22: Current gas mix and future scenarios up to 2030[a] (DECC, 2013c; Williams et al., 2011).

Gas source	**Current situation (2012)**		**Future scenario (2030)**			
			Low penetration		High penetration	
	10^9 Nm^3	%	10^9 Nm^3	%	10^9 Nm^3	%
Conventional gas	77.4	85.1	59	67.0	59	67.0
UK North Sea	*41.7*	*45.8*	*16*	*18.2*	*16*	*18.2*
Norway	*27.2*	*29.9*	*33*	*37.5*	*33*	*37.5*
Netherlands	*7.2*	*7.9*	*10*	*11.4*	*10*	*11.4*
Belgium	*1.3*	*1.4*	*0*	*0*	*0*	*0*
LNG (Qatar)	13.6	14.9	25	28.4	4	4.5
UK shale gas	0	0	4	4.5	25	28.4

[a] The figures include consumption of both heat and electricity generation; 25% is used for electricity generation.

3. Results and discussion

The impacts of shale gas electricity are discussed, first in comparison to conventional gas and LNG because shale gas is expected to replace both domestic conventional gas and imported LNG in the future (HM Treasury, 2013). This is then followed by a comparison with the literature and other options in the UK electricity mix. In a subsequent section, a sensitivity analysis explores the influence of some assumptions on the results. The final section examines the effect that shale gas could have on the impacts from electricity generation in the future, using the scenarios defined above.

3.1. Shale gas versus conventional gas and LNG

3.1.1. Abiotic depletion potential of elements (ADP_e)

The ADP_e of shale gas electricity is estimated at 0.68 mg Sb_{-Eq}./kWh in the central case (Figure 15). This is almost three times higher than electricity from conventional gas (0.24 mg Sb_{-Eq}./kWh) and LNG (0.26 mg Sb_{-Eq}./kWh). The reason for this is the chemicals used in the drilling fluid, particularly barite, which altogether contribute 98% to this impact with the remaining 2% being from the power plant (Figure 16). However, the depletion of elements from shale gas ranges widely, from 0.05 mg Sb_{-Eq}./kWh in the best case to 10 mg Sb_{-Eq}./kWh in the worst. Therefore, if the total amount of drilling fluid can be kept at the minimum of 10.6 kt or 0.4 L per MWh as in the best case scenario considered here (Table 17), the ADP_e of shale gas electricity would be almost five times lower than for conventional gas and LNG.

3.1.2. Abiotic depletion potential of fossil fuels (ADP_f)

In the central case, the depletion of fossil fuel resources by shale gas is close to that of conventional gas (6.6 vs. 6.3 MJ/kWh). The slightly higher value is because of the longer drilling lengths and hydraulic fracturing, which both use diesel-powered equipment. The worst option is LNG, which has a 12-17% higher impact than the other two. This is due to the energy-intensive liquefaction and regasification processes. However, in the worst case, the impact from shale gas is 65% higher than for LNG. This is largely because of the low EUR, which is to be expected given that this impact is mainly (96%) caused by gas extraction (Figure 16). In the best case, at the maximum EUR, shale gas is slightly better (by 5%) than conventional gas because of the larger EUR.

3.1.3. Acidification potential (AP)

Electricity from shale gas has the lowest AP of the three options considered, as shown in Figure 15: 0.4 g $SO_{2\text{-Eq}}$./kWh in the central case compared to 1.7 and 3.4 g $SO_{2\text{-Eq}}$./kWh for conventional and gas and LNG, respectively. This can be attributed to shale gas being less sour and of a higher quality than conventional gas, leading to lower emissions of acid gases from power plants, which contribute 45% to this impact (Figure 16). The *“sweetness"* of shale gas is due to the greater depths of shale rock and higher temperature and pressure, which are unsuitable for the bacteria that decompose organic material to produce hydrogen sulfide, the process that takes place in conventional gas reservoirs (Clarke et al., 2014; Kallmeyer and Boetius, 2004). At the top of the range, the AP is 66% higher than for conventional gas because of the low EUR assumed in the worst case; however, it is still 17% lower than electricity from LNG. In the best case, the relative difference between conventional gas and LNG is much greater: 86 and 93% in favor of shale gas, respectively.

3.1.4. Eutrophication potential (EP)

Shale gas electricity has an EP of 170 mg $PO_{4\text{-Eq}}$./kWh in the central case, which is 2.8 times higher than conventional gas and LNG (Figure 15); in the worst case, it is 30 times higher. This can be attributed to the disposal of drilling waste which contributes 38% to this impact. The main reason is naturally occurring phosphorus in the soil extracted during drilling. However, if the amount of waste can be minimised, as in the best case (Table 17), shale gas becomes comparable to both conventional gas and LNG: 70 vs. 60 mg $PO_{4\text{-Eq}}$./kWh.

3.1.5. Freshwater aquatic ecotoxicity potential (FAETP)

The FAETP of shale gas is estimated in the central case at 13 g DCB_{-Eq}./kWh (DCB = dichlorobenzene), which is five and three times higher than conventional gas and LNG, respectively. In the worst case, shale gas is 56 and 35 times higher, respectively. This is largely due to the toxicity of the drilling fluid after its disposal, which contributes 51% to the FAETP. However, similar to the EP for the minimum amount of drilling waste assumed in the best case, the FAETP becomes comparable to conventional gas at 3 $gDCB_{-Eq}$./kWh.

3.1.6. Global warming potential (GWP)

In the central case, electricity from shale gas has a GWP of 460 g CO_{2-Eq}./kWh; this is higher than for conventional gas (420 g CO_{2-Eq}./kWh) but lower than for LNG (490 g CO_{2-Eq}./kWh for LNG; Figure 15). The longer drilling lengths and hydraulic fracturing are the reasons for shale gas having a higher GWP than conventional gas. Conversely, energy-intensive liquefaction and regasification lead to a greater impact from LNG than from shale gas. In the best case, shale gas is the best option with 420 g CO_{2-Eq}./kWh because of the high EUR assumed. In the worst case (low EUR), the impact is twice as high as the other two options.

Despite the different assumptions and system boundaries, the GWP values estimated here (420-930 g CO_{2-Eq}./kWh) compare well with those reported in the literature, most of which fall in the range of 400-800 g CO_{2-Eq}./kWh (Burnham et al., 2012; Dale et al., 2013; Hultman et al., 2011; Jiang et al., 2011).

3.1.7. Human toxicity potential (HTP)

At 54 g DCB_{-Eq}./kWh in the central case, shale gas has a 37-43% higher HTP than electricity from the other two gas options (Figure 15). This can be attributed to the disposal of drilling fluid, which contributes 21% to the total impact (Figure 16) because of the toxic substances such as barite and acetone. Therefore, the results are sensitive to the amount of the drilling fluid considered in the worst case, the HTP is seven times higher than in the best case, with the latter being almost the same as conventional gas and LNG (38 g DCB_{-Eq}./kWh).

3.1.8. Marine aquatic ecotoxicity potential (MAETP)

A similar pattern is found for the MAETP as for the HTP, for which shale gas is the worst option by a large margin: 37 kg DBD_{-Eq}./kWh in the central case versus 0.5 and 0.9 kg DBD_{-Eq}./kWh for conventional gas and LNG, respectively. Like the HTP, the disposal of the drilling fluid is the main contributor in this impact (47%). If the amount of drilling fluid is at the maximum value considered in the worst case (Table 17), the impact is tenfold higher than in the central case; even for the minimum amount in the best case, the MAETP is still 13 times higher than for conventional gas and seven times greater than for LNG.

3.1.9. Ozone layer depletion potential (ODP)

This impact is similar for shale and conventional gas (17 and 19 µg $R11_{-Eq}$./kWh, R11 = trichlorofluoromethane), which is around three times higher than LNG. This is because LNG is shipped, avoiding the need for flame retardants and coolants used in the pipeline distribution of conventional and shale gas; these contribute 77% to the ODP of shale gas (Figure 16). In the best case, the ODP of shale gas is still double that of LNG and in the worst, its impact is three times higher than conventional gas.

3.1.10. Photochemical oxidants creation potential (POCP)

The POCP for shale gas ranges from 69-402 mg C_2H_{4-Eq}./kWh, with the central value estimated at 84 mg C_2H_{4-Eq}./kWh. The latter is 2.5 times higher than conventional gas, which is the best option, and 20% greater than LNG. This is largely due to fugitive methane emissions (35%) as well as the emissions of volatile organic compounds from the equipment used for well drilling. In the best case, in which the fugitive emissions are the lowest, the POCP of shale gas approaches that of LNG; the impact from the latter is caused by refrigerants such as ethane and propane used in the liquefaction stage.

3.1.11. Terrestrial ecotoxicity potential (TETP)

Shale gas has the highest TETP: 1.7 g DCB_{-Eq}./kWh in the central case versus 0.2 g DCB_{-Eq}./kWh for the other two gas options. As for the other toxicity-related impacts, this is because of the disposal of the drilling waste which contributes 87% to this impact (Figure 16). However, in the best case, the TETP of shale gas is identical to that of conventional gas and LNG because of the lower amount of drilling waste assumed. In contrast, for the maximum value of drilling waste in the worst case, the impact increases to 23.4 g DCB_{-Eq}./kWh, which is 117 times higher than the other two options.

In summary, the results for the central case suggest that electricity from shale gas has higher impacts than conventional gas and LNG. However, its GWP is lower than LNG (by 7%) so using it instead of LNG could help reduce GHG emissions. The main contributors to the impacts are the drilling (the drilling fluid and its disposal) and power plant (combustion of gas) stages. By comparison, the contribution of hydraulic fracturing is small: 1-5% for most impacts and 16% for acidification (Figure 16). The contribution of fugitive methane emissions is also significant for the POCP.

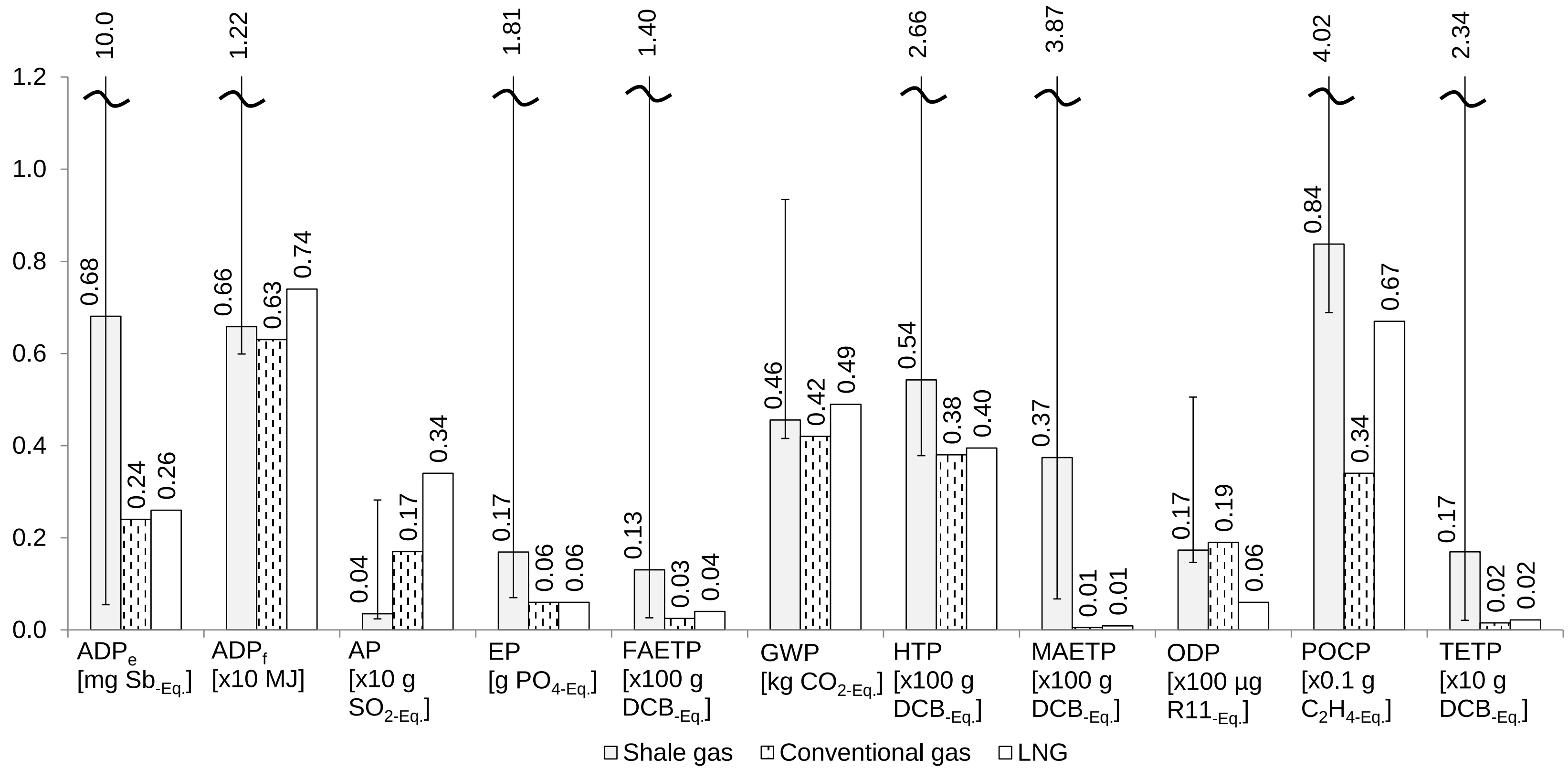


Figure 15: Environmental impacts of shale gas in comparison with conventional gas and LNG. All impacts expressed per kWh of electricity generated. For shale gas, the height of the chart bars represents impacts for the central case. The error bars correspond to the best (minimum) and worst (maximum value) case, respectively, estimated using the values in Table 17 and the related data in Appendix B. Some impacts have been scaled to fit. To obtain the original values, multiply by the factor shown against relevant impacts.

[ADP$_e$: Abiotic resource depletion (elements); ADP$_f$: Abiotic resource depletion (fossil); AP: Acidification potential; EP: Eutrophication potential; FAETP: Freshwater aquatic ecotoxicity potential; GWP: Global warming potential; HTP: Human toxicity potential; MAETP: Marine aquatic ecotoxicity potential; ODP: Ozone layer depletion potential; POCP: Photochemical oxidants creation potential; TETP: Terrestrial ecotoxicity potential.]

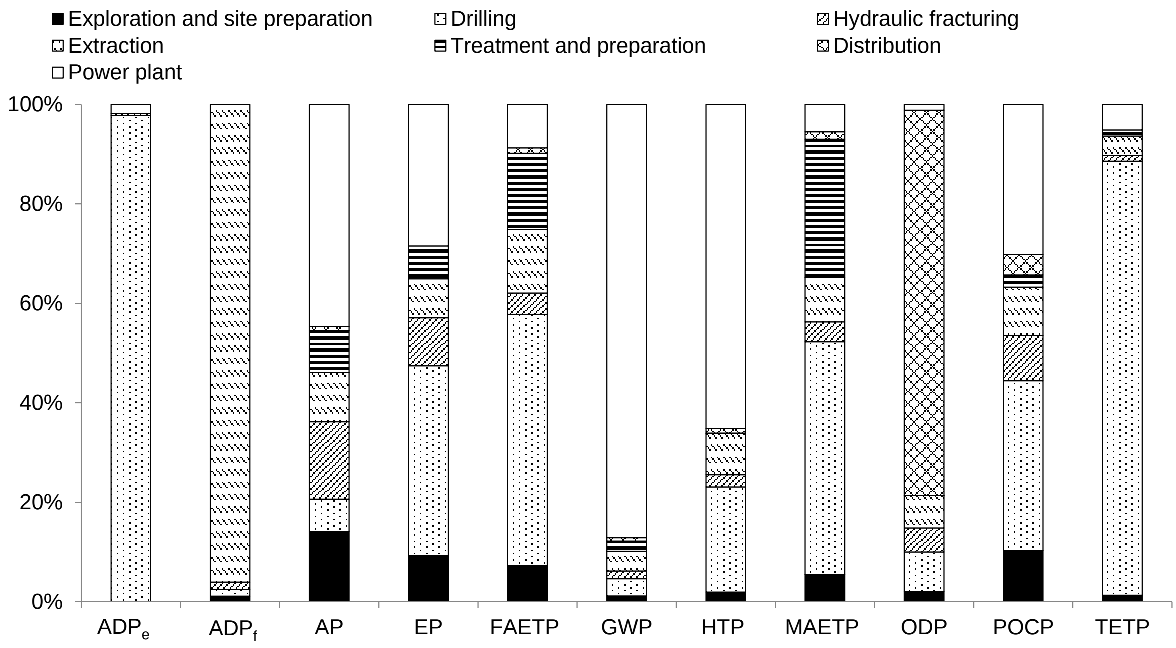


Figure 16: Contribution of different life cycle stages to the impacts from shale gas electricity. Drilling includes drilling fluid, equipment and waste disposal. Hydraulic fracturing comprises fracturing fluid, pumping power and equipment. For impacts nomenclature, see Figure 15.

3.2. Comparison of results with the literature

As mentioned in the previous chapter, there is only one other study which considers the environmental impacts of shale gas for a range of impacts besides the GWP. This is the study by the supervisors of this PhD project (Stamford and Azapagic, 2014) and considers UK shale gas extraction and utilisation for electricity generation. In comparison to their results, this study found the impacts (in the central case) to be on par in four impact categories: ADP_f, EP, GWP and ODP (Figure 17). The minimum and maximum values, representing the best and worst case scenarios, respectively, are also on par with the exceptions of the EP and GWP. This study estimated the maximum EP to be higher while the maximum GWP is lower. This is the result of differences in data and assumptions as discussed further in this section. For the remaining seven impact categories, there is a small but significant (31% for MAETP) to substantial difference (17-fold for ADP_e) in the results of the two studies. The differences in the results can be attributed to differences in the assumptions and data used.

The study by Stamford and Azapagic (2014) modelled their shale gas well based on data from Cuadrilla Resources for their Preese Hall 1 well, while this study used US data. The Preese Hall 1 well is the exploration well drilled by Cuadrilla Resources in 2011 and is the only well to be hydraulically fractured (to date at the time of writing) in the UK. As the well is an exploration well, it is not horizontally drilled and is smaller in size to commercial wells (which this study is based on). This is the main reason for the large difference in ADP_e and the ecotoxicity indicators (Figure 17), as this study considers a larger well which uses more drilling fluid and therefore produces more drilling waste. This is also the reason why the maximum EP calculated in this study is 61% higher than that of Stamford and Azapagic (2014).The exception is the TETP for which this study is 1.95 times smaller (Figure 17). This is because of difference in drilling waste management assumptions; Stamford and Azapagic (2014) assumes more waste is disposed of by land spreading. The differences in well size and drilling waste management also result in the maximum values for the ADP_e and ecotoxicities varying between the two studies.

Another key difference in the data and assumptions is the composition of the gas produced. The composition assumed in this study is *"sweeter"*, resulting in the AP calculated being 65% lower in the central case and 61% lower in the maximum (Figure 17). This also affects the POCP, as the removal of H_2S can contribute significantly towards the POCP because of VOC emissions from equipment (Stamford and Azapagic, 2014). As the gas in this study contains less H_2S, less gas is processed to remove H_2S, resulting in the POCP being 2.7 times smaller in the central case and 6.2 times smaller in the maximum (Figure 17).

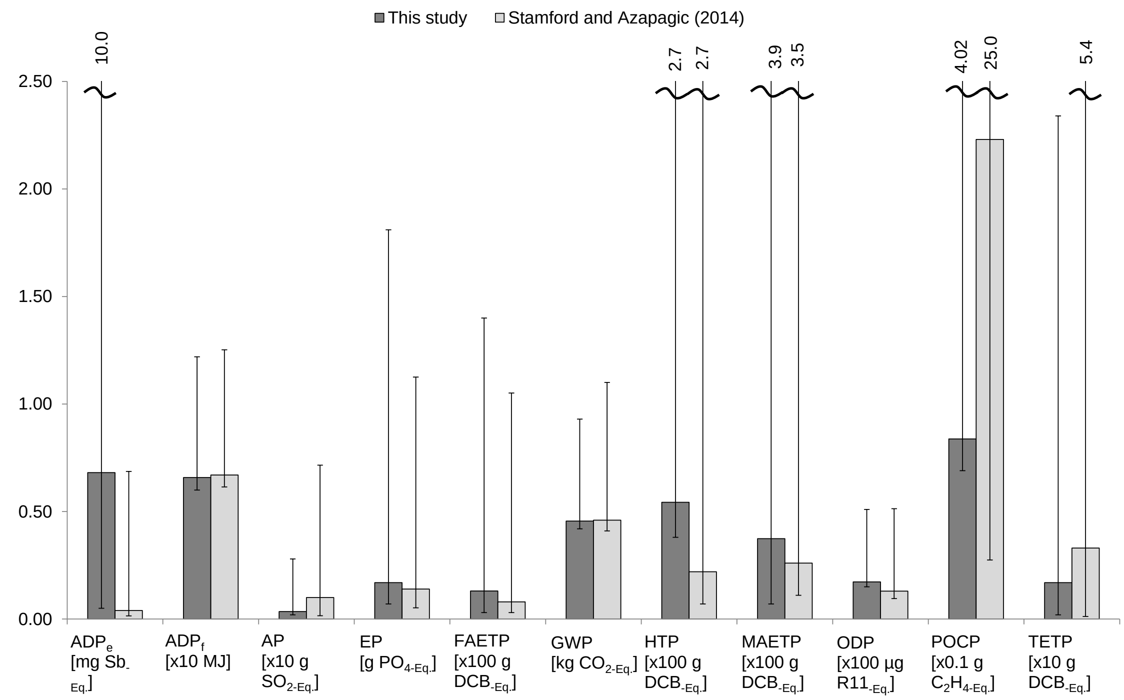


Figure 17: Comparison of environmental impacts to results by Stamford and Azapagic (2014). All impacts expressed per kWh of electricity generated. The height of the chart bars represents impacts for the central case. The error bars correspond to the best (minimum) and worst (maximum value) case, respectively. Some impacts have been scaled to fit. To obtain the original values, multiply by the factor shown against relevant impacts. For impacts nomenclature, see Figure 15.

3.3. Shale gas versus other electricity options

The results for the central case, as shown in Figure 18, indicate that shale gas electricity has lower environmental impacts than coal, except for the ADP_e and ODP. This is due to the impacts of coal mining and waste generated during both mining and electricity generation. The ADP_e is 16 times higher for shale gas than coal because of the use of chemicals such as barite in the drilling fluid. However, solar PV is the worst option for this impact owing to the metallisation coat used in the manufacture of solar cells. In addition, most other impacts from solar PV are higher than shale gas, except for the ADP_f, GWP, POCP and TETP. The ODP is three times higher for shale gas than for coal owing to the fire retardants and coolants used in transporting the gas, but nuclear power has a higher ODP, whereas this impact from solar PV is equal to that of shale gas. In comparison to wind, shale gas is a better option for the FAETP, HTP and TETP because of the impacts associated with the materials used to manufacture the wind turbines. Similarly, shale gas is a better option than biomass for the AP, EP, FAETP, HTP, MAETP, POCP and TETP because of the cultivation and processing of energy crops and their combustion in the power plant. The impacts of shale gas are all higher than those of nuclear power, except for the FAETP, HTP, MAETP and ODP because of uranium mining and fuel enrichment. Finally, the best option across all the categories is hydroelectricity, the impacts of which are 8-188 times lower than shale gas.

In the worst case (Figure 18), shale gas is still a better option than coal for six out of 11 impacts. In addition to the ADP_e, the other four impacts that are higher for shale gas are the ADP_f (by 4%), ODP (nine times higher), POCP (41%) and TETP (13 times). For the former two, this is due to the low EUR; for the POCP it is because of high fugitive emissions of methane and for the TETP, it is because of the drilling waste assumed in the worst case. Compared to the other options, all impacts from shale gas are higher except for the ADP_e, which is slightly lower than solar PV (by 8%).

In the best case, most of the impacts of shale gas are lower than solar PV, except for the ADP_f, GWP and POCP. These are also higher for shale gas than for wind, in addition to the AP, EP and ODP, with the remaining impacts being lower for shale gas. The ADP_f, GWP and ODP are also worse for shale gas than for biomass in the best case, but the remaining eight impacts are lower for shale gas. In comparison to nuclear power, shale gas is a better option for six impacts: ADP_e, FAETP, HTP, MAETP, ODP and TETP. Against coal, shale gas is a better option for most impacts in the central case, except for the ADP_e and ODP. However, unlike the central case, in the best case shale gas has three impacts lower than hydroelectricity: FAETP, MAETP and TETP.

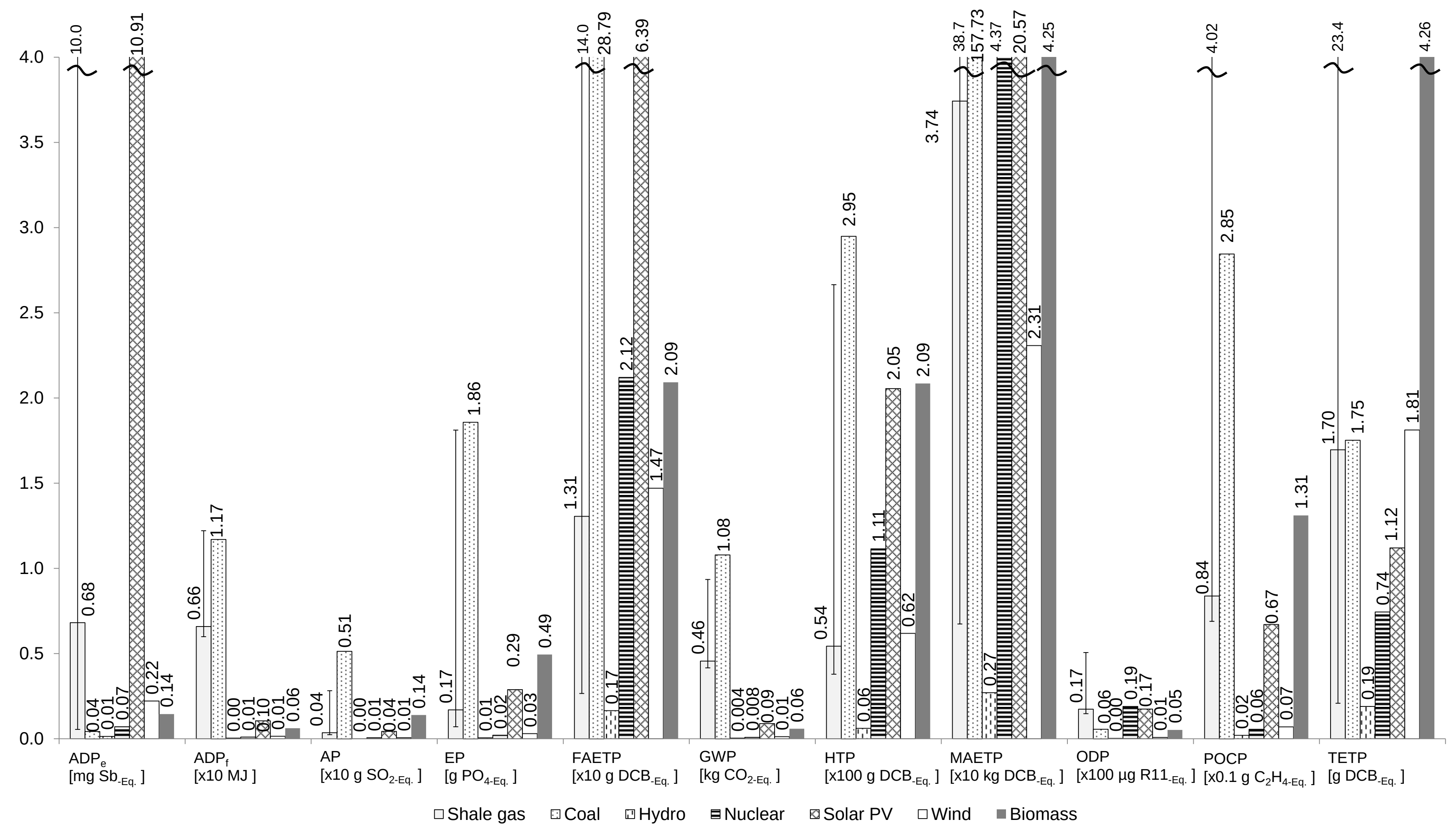


Figure 18: Environmental impacts of shale gas in comparison with other electricity options in the UK. All impacts expressed per kWh of electricity generated. For shale gas, only the central values are shown. For the best and worst case values as well as the impacts nomenclature, see Figure 15. Some impacts have been scaled to fit. To obtain the original values, multiply by the factor shown against relevant impacts.

3.4. Sensitivity analysis

Three parameters are examined in the sensitivity analysis: drilling fluid, fugitive methane emissions and land use change on greenhouse gas emissions. The first is considered as it is a major contributor to most impacts (Figure 16) and the other two because these values are uncertain (Howarth et al., 2011; Karion et al., 2013; Wigley, 2011; Bond et al., 2014). Fugitive methane emissions were also found to influence the POCP significantly.

3.3.1 Drilling fluid

Different amounts of water-based drilling fluid have already been considered above in the best, central and worst cases. Here, an alternative is considered: oil-based drilling fluid, which is more stable than the water-based fluid as well as being better suited for directional drilling (Caenn et al., 2011). Despite these advantages, oil-based fluid is more expensive and consequently, water-based fluids are often preferred and used. However, it is unclear which of the two options may be preferable environmentally and how the impacts from shale gas would be affected if oil-based fluid was used instead of water-based. These results are displayed in Figure 19 for the central case. The composition of the oil-based fluid is assumed to be the same as that used by IGas Energy at their Barton Moss site in the UK (Russell and Hargreaves, 2013) (Table B11 in Appendix B).

The results suggest that the type of drilling fluid does not affect the impacts much, with the oil-based fluid having on average 5% higher impacts, ranging from 1% higher MAETP to 22% greater TETP; the GWP and ODP are the same for both fluids (Figure 19). The exception is the ADP_e, which is 2.7 times higher for the water-based fluid because the oil-based liquid uses fewer chemical additives.

3.3.2 Fugitive emissions of methane

To assess the effect of fugitive emissions, the following two cases have been considered, in addition to the best, central and worst cases:

- a maximum value of 312,200 m^3 of methane emissions over the lifetime of the well as estimated by the US EPA (EPA, 2012), equivalent to a 0.26% loss of shale gas for the EUR of 122 Mm^3 in the central case; and
- no fugitive emissions, whereby the methane is captured and separated from the wastewater; known as ‘green completion’, operators will be required to use this technique for extraction of shale gas in the UK (UKOOG, 2013).

For both emission values, all other assumptions are the same as in the central case in Table 17.

The results suggest that the only impact affected by the fugitive emissions of methane is the POCP, which increases by 17% for the maximum emissions, relative to the central case. For the case with no fugitive emissions, the POCP is reduced by 35%. Note that the GWP is not affected (<1% change) as fugitive emissions contribute only 0.9% to this impact; by comparison, the combustion of gas in the power plant contributes 87.1%. As discussed above, these findings are based on the maximum loss rate of 0.26% of the EUR as estimated by US EPA data (EPA, 2012). However, Howarth et al. (Howarth et al., 2011) found fugitive emissions to be more influential but they assumed unrealistically high emissions of 3.6-7.9%, which have been refuted by several authors (e.g. Cathles et al. (2012)).

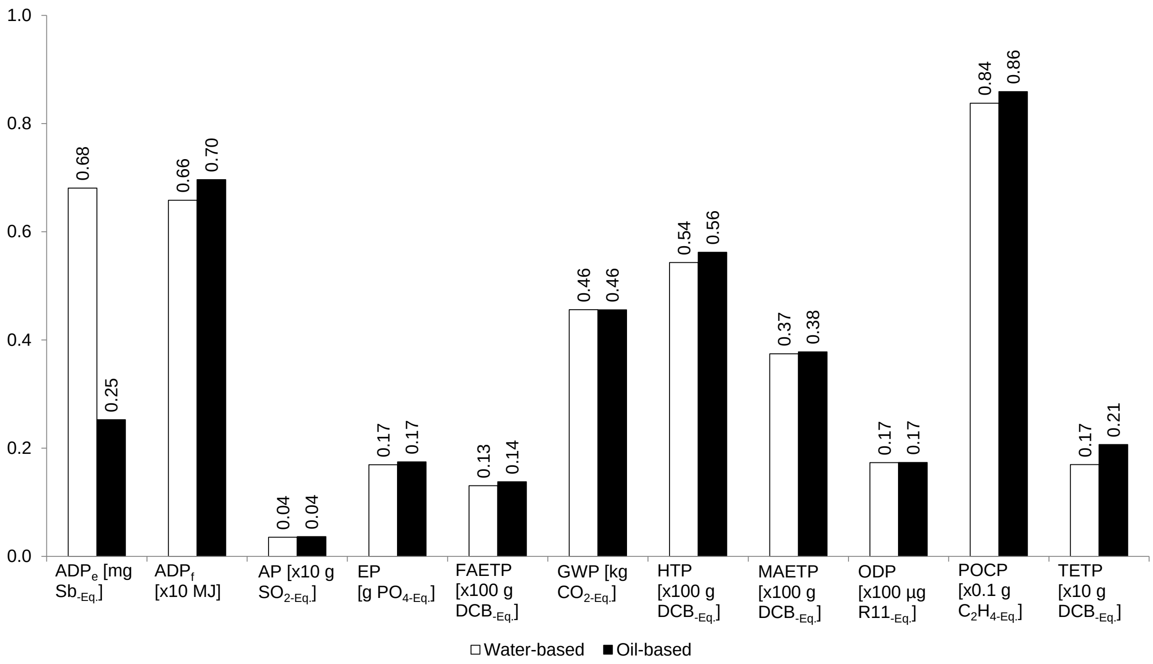


Figure 19: Comparison of impacts of shale gas for water and oil-based drilling fluids. The results refer to the central case. All impacts expressed per kWh of electricity generated. For impacts nomenclature, see Figure 15. Some impacts have been scaled to fit. To obtain the original values, multiply by the factor shown against relevant impacts.

3.3.3 Land use change on greenhouse gas emissions

The impact of land use change on greenhouse gas emissions was not considered in the LCA because the UK currently does not have any operating shale gas wells. To assess the effect of land use change, four cases are analysed: forestry land (annual cropland), grassland (annual cropland), forestry (perennial cropland) and grassland (perennial cropland) (BSI, 2011). Greenhouse gas emissions are calculated using emission factors from BSI (2011) and further details can be found in Appendix B. The emission factors consider GHG emissions from the disturbance of soil and the displacement of CO_2 absorption capacity. The results of the sensitivity analysis found that the impact of land use change depends on both the type of land being transformed as well as the productivity of the well. Between 0.02-9.88 g $CO_{2\text{-}Eq}$. could be added to the GWP of shale gas electricity (per kWh electricity), as shown in Table 23, which could increase the GWP by between 2.08 $x10^{-3}$-2.38 %. This is a small increase and therefore the effect of land use change will likely not contribute significantly to the GWP. This is for the four land types considered. A study by Bond et al. (Bond et al., 2014) found that when peat soil is considered, the impact is much greater, due to peat bog soil being a much better at storing carbon than other soil types (Agus et al., 2011; Hagon et al., 2013).

Table 23: Comparison of land use change impacts on greenhouse gas emissions for shale gas electricity.

Land type	**Minimum EUR**	**Average EUR**	**Maximum EUR**
	(g $CO_{2\text{-}Eq}$. per kWh)		
Forestry (annual cropland)	9.88	0.81	0.08
Grassland (annual cropland)	2.56	0.21	0.02
Forestry (perennial cropland)	7.32	0.60	0.06
Grassland (perennial cropland)	2.45	0.20	0.02

3.5. Future gas and electricity scenarios

This section considers the role that shale gas could play in a future electricity mix in the UK and how this may affect the environmental impacts of electricity generation. First, the results for the future gas sources defined in Table 22 are considered, followed by the electricity mix as specified in Table 21 .

3.5.1. Future gas scenarios

Two gas scenarios are considered in 2030: low and high shale gas production in the UK. The results shown in Figure 20 suggest that for both scenarios the impacts are higher than they are today. This is due to a combination of two factors: the increase in gas imports that is required as domestic production continues to decline and the introduction of shale gas. On average, the impacts are 38% higher for the low shale and 2.5 times higher for the high shale scenario, compared to the current situation. The most affected categories in both scenarios are the ADP_e which increases by 2.3 and nine times, respectively and the toxicities, which are 13% to four times higher across the two scenarios. This is largely due to the drilling waste disposal in the life cycle of shale gas as discussed previously.

Comparing the two scenarios, when shale gas replaces LNG (high shale gas penetration scenario), eight out of 11 impacts increase from 7% to 3.9 times: the ADP_e, EP, FAETP, HTP, MAETP, ODP, POCP and TETP. Again, the toxicity-related categories are the most affected. However, the remaining three impacts are reduced: GWP, AP and ADP_f by up to 3%. Therefore, although shale gas could help to reduce the GWP compared to LNG, toxicity as well as the depletion of elements and ozone would increase.

3.5.2. Future electricity scenarios

Figure 21 shows that eight out of 11 impacts (the ADP_f, AP, EP, FAETP, GWP, HTP, MAETP, POCP) from electricity generation decrease for both scenarios compared to the current mix, which is largely due to the anticipated reduction in the use of coal and growth in renewable and nuclear capacity (Table 21). The reductions in both scenarios range from 35% for the HTP to 87% for the MAETP; the GWP is lower by 73% for both future scenarios. However, the ADP_e, ODP and TETP increase by 2.9-3.3 times, 10-15% and 15-22%, respectively. This is attributed to the higher penetration of wind and solar PV (ADP_e), gas (ODP) and wind (TETP).

Overall, it can be seen that there is little difference between the two scenarios, which suggests that the contribution of shale gas to the impacts of future electricity generation would be small. The greatest effect is found for the ADP_e which increases by 15% for the high penetration of shale gas compared with the low. Most other impacts also increase but by a smaller amount (<6%).

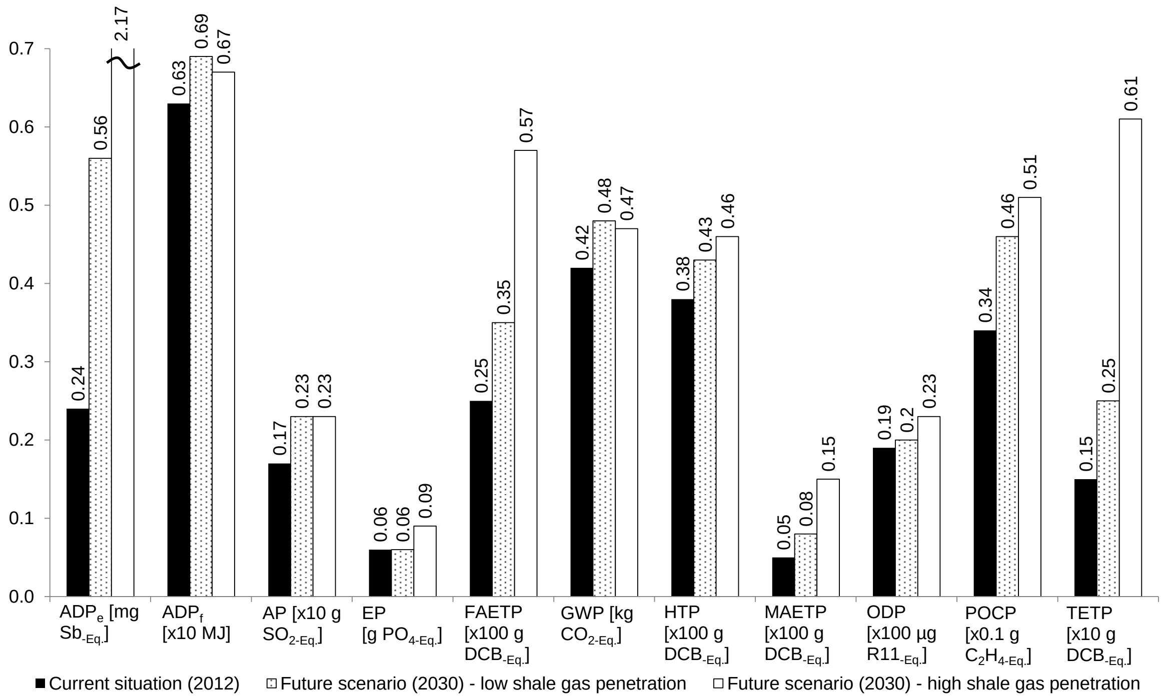


Figure 20: Environmental impacts of the future gas scenarios compared to the current situation. All impacts expressed per kWh of electricity generated. For the current situation and future scenarios, see Table 22. Some impacts have been scaled to fit. To obtain the original values, multiply by the factor shown against relevant impacts. For impacts nomenclature, see Figure 15.

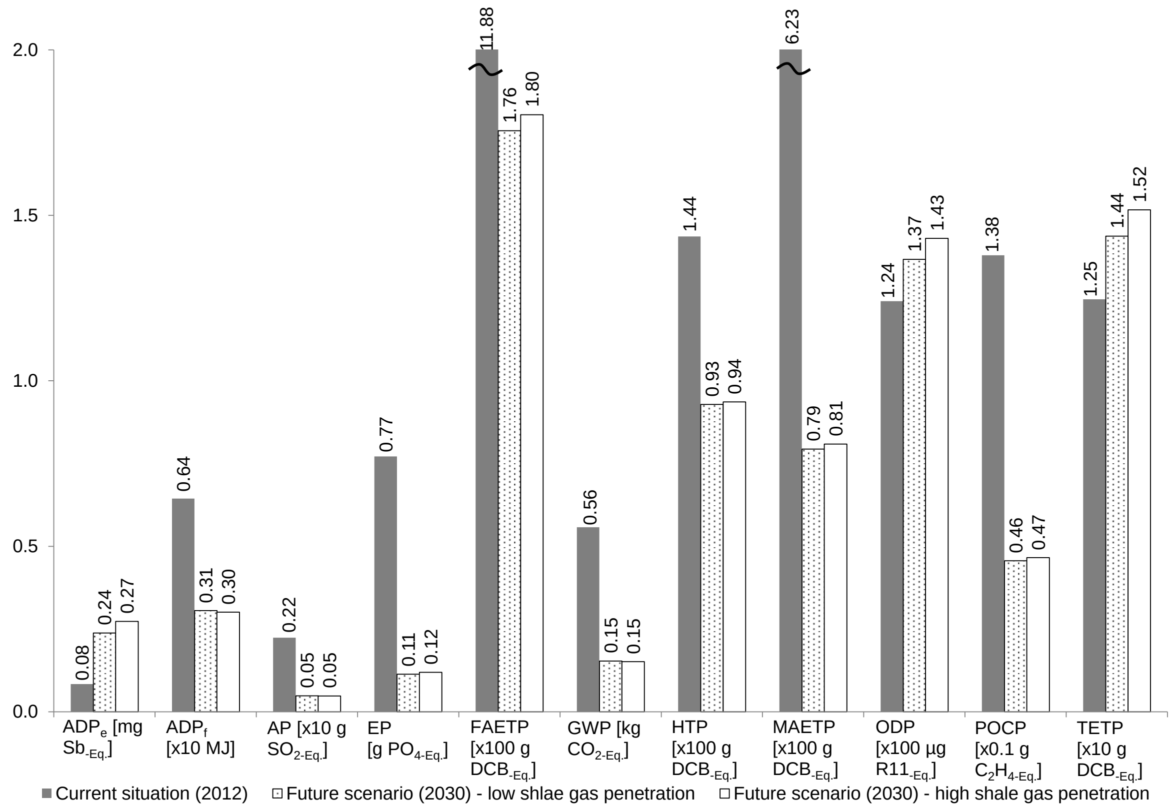


Figure 21: Environmental impacts of future (2030) electricity scenarios incorporating different contributions from shale gas specified in Table 21. All impacts expressed per kWh of electricity generated. For definition of the current and future scenarios see Table 21. The low and high penetration scenarios refer to the contribution of shale gas in 2030 as specified in Table 22. Some impacts have been scaled to fit. To obtain the original values, multiply by the factor shown against relevant impacts. For impacts nomenclature, see Figure 15.

4. Conclusions

This study has considered the life cycle environmental impacts of shale gas used for electricity generation in the UK. The impacts have been compared to a number of current electricity sources, including other fossil fuels, nuclear and renewables. Future gas and electricity scenarios have been considered up to 2030 to examine the role that shale gas could play in the future as well as its potential contribution to the impacts.

The results suggest that in the central case, shale gas has higher environmental impacts than conventionally produced gas and liquefied natural gas (LNG), but has a lower global warming potential (GWP) than LNG (by 7%). This means that if it is used to replace LNG, shale gas could help to reduce greenhouse gas (GHG) emissions.

Shale gas also has lower impacts in the central case than coal for all categories, except for the abiotic depletion potential of elements (ADP_e) and the ozone layer depletion potential (ODP). Therefore, if shale gas were to replace coal as suggested by the

Government, it would lead to a substantial reduction in most environmental impacts per kWh of electricity generated, with the GWP being reduced by 58%. However, the ADP_e would be 16 times higher and the ODP three times higher. Most impacts for solar photovoltaic (PV) are also higher than those from shale gas, except for the ADP fossil, GWP, photochemical oxidants creation potential (POCP) and terrestrial ecotoxicity potential (TETP). Similarly, most impacts from biomass are higher, except the ADP_e, abiotic depletion potential of fossil fuels (ADP_f), GWP and ODP. In comparison with wind, shale gas is the worse option for most impacts except for the freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP) and TETP. It also has higher impacts than nuclear power, bar the FAETP, HTP, marine aquatic ecotoxicity potential (MAETP) and ODP. Overall, the best option across all the categories is hydroelectricity, for which the impacts are 8-188 times lower than shale gas.

In the best case, shale gas is a better option for nine impacts than electricity from coal and for eight impacts than solar PV and biomass. Against nuclear power and wind, six and five impacts are lower for shale gas, respectively, whereas against hydroelectricity, it is better for three impacts. However, assuming the worst case scenario, shale gas is the worst option across all the impacts. The exceptions are coal, against which shale gas is better for six impacts and solar PV, which has a higher ADP_e.

The main contributors to the impacts of shale gas are the drilling fluid and its disposal as well as the combustion of gas in the power plant; the contribution of hydraulic fracturing is small (5%). The results indicate that minimising the amount of drilling fluid used could reduce the impacts by 9-92%. If oil-based drilling fluid was used instead of the more commonly used water-based fluid, the impacts would increase on average by 5%. The exception is the ADP_e, which is 2.7 times higher for the water-based fluid. Fugitive emissions of methane have little effect on the impacts (except for the POCP), as does the effect of land use change on GWP.

If shale gas were to replace LNG in a future gas mix in the UK, eight out of 11 impacts would increase by between 15% and 3.9 times: the ADP_e, eutrophication potential (EP), FAETP, HTP, MAETP, ODP, POCP and TETP. However, the GWP, ADP_f and acidification potential (AP) would see a reduction by up to 3%. Therefore, although shale gas can help reduce the GWP compared to LNG, the toxicities as well as the depletion of elements and the ozone layer would increase.

Within an electricity mix, shale gas would make little difference to the environmental impacts of electricity generated even for the high penetration considered here. The greatest effect would be on the ADP_e, which would increase by 15% for a high compared to a low penetration of shale gas. The other impacts would also increase by 1-6%; the GWP would be unaffected.

Therefore, these results suggest that in the medium-term shale gas cannot help towards meeting the UK GHG emission targets, even if it were to replace coal and LNG and that other options, such as certain renewables and nuclear power, must be prioritised instead. However, other drivers such as the security of energy supply and future costs of energy must also be taken into account if, as argued by the UK Government, shale gas can help improve these, then the future role of shale gas in the UK will depend on the perceived importance of these drivers against climate change targets.

References

Agus, F., Hairiah, K. and Mulyani, A. **2011**. *Measuring carbon stocks in peat soils: Practical guidelines*. *World Agroforestry Centre (ICRAF) Southeast Asia Regional Program, Indonesian Centre for Agricultural Land Resources Research and Development*. Bogor, Indonesia. Retrieved from: http://www.worldagroforestry.org/downloads/Publications/PDFS/MN17335.PDF.

API. **2000**. *Overview of exploration and production waste volume and waste management practices in the United States*. *American Petroleum Institute (API)*. Washington DC. Retrieved from: http://www.api.org/~/media/files/ehs/environmental_performance/icf-waste-survey-of-eandp-wastes-2000.pdf?la=en.

Bond, C. E., Roberts, J., Hastings, A., Shipton, Z. K., Joao, E. M., Kyzy, J. T. and Stephenson, M. **2014**. *Life-cycle assessment of greenhouse gas emissions from unconventional gas in Scotland*. September, 2014. *ClimateXChange*. Glasgow, UK. Retrieved from: http://www.climatexchange.org.uk/reducing-emissions/understanding-potential-climate-impact-unconventional-gas-extraction-scotland.

BSI. **2011**. *PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of good and services*. *British standards Institution (BSI)*. London, UK. Retrieved from: http://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf.

Burnham, A., Han, J., Clark, C. E., Wang, M., Dunn, J. B. and Palou-Rivera, I. **2012**. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. *Environmental Science and Technology*, 46, 619-627.

Caenn, R., Darley, H. C. H. and Gray, G. R. **2011**. *Composition and properties of drilling and completion fluids* 6th, Oxford, UK: Gulf Professional Publishing, Elsevier.

Cathles, L., M. III, Brown, L., Taam, M. and Hunter, A. **2012**. A commentary on "The greenhouse-gas footprint of natural gas in shale formations" by R.W. Howarth, R. Santoro, and Anthony Ingraffea. *Climatic Change*, 113, 525-535.

Clark, C., Burnham, A., Harto, C. and Horner, R. **2013**. *Hydraulic fracturing and shale gas production: Technology, impacts, and regulations*. *Argonne National Laboratory*. Oak Ridge, TN, USA. Retrieved from: http://www.afdc.energy.gov/uploads/publication/anl_hydraulic_fracturing.pdf.

Clarke, H., Turner, P. R. and Bustin, M. **2014**. *Unlocking the resource potential of the Bowland Basin, NW England (Conference)*. SPE/EAGE European Unconventional Resources Conference and Exhibition. 25-27 February 2014 Vienna, AT. Society of Petroleum Engineers (SPE).

Coffey Environments. **2011**. *Environmental impact statement: Arrow LNG plant*. *Arrow Energy*. Brisbane, AU. Retrieved from: https://www.arrowenergy.com.au/__data/assets/pdf_file/0014/12308/117147_Presentation_-_Coffey_Arrow_LNG_Plant_EIS_Environment_Workshop.pdf.

Cohen, H. K. **2013**. *The shale gas paradox: Assessing the impacts of the shale gas revolution on electricity markets and climate change*. Bachelor, Harvard College.

Cuadrilla Resources. **2017**. *Fracturing fluid* [Online] Preston, UK. Available: http://www.cuadrillaresources.com/what-we-do/hydraulic-fracturing/fracturing-fluid/ [Accessed 2017 February].

Dale, A. T., Khanna, V., Vidic, R. D. and Bilec, M. M. **2013**. Process based life-cycle assessment of natural gas from the Marcellus Shale. *Environmental Science and Technology*, 47, 5459-5466.

DECC. **2013a**. *Digest of United Kingdom energy statistics 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/279523/DUKES_2013_published_version.pdf.

DECC. **2013b**. *Power stations in the United Kingdom, May 2013 (DUKES 5.11)*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/publications/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes.

DECC. **2013c**. *UK energy in brief 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224130/uk_energy_in_brief_2013.PDF.

DECC. **2013d**. *Updated energy and emissions projections 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/239937/uep_2013.pdf.

Deville, J. P., Fritz, B. and Jarrett, M. **2011**. Development of water-based drilling fluids customized for shale reservoirs. *SPE Drilling and Completion*, 26, 484-491.

Ecoinvent Centre. **2010**. *Ecoinvent datadata v2.2.* Zurich, CH Retrieved from: http://www.ecoinvent.org/database/.

EIA.**2014**.*Average depth of crude oil and natural gas wells*. Accessed from: http://www.eia.gov/dnav/pet/pet_crd_welldep_s1_a.htm.

EPA. **2012**. *Oil and natural gas sector: Standard of performance for crude oil and natural gas production, transmission, and distribution*. *US Environmental Protection Agency (EPA)*. Washington DC. Retrieved from: https://www3.epa.gov/airquality/oilandgas/pdfs/20120418tsd.pdf.

FracFocus. **2014**. *What chemicals are used* [Online] Oklahoma City, OK, USA: Ground Water Protection Council (GWPC). Available: http://fracfocus.org/chemical-use/what-chemicals-are-used [Accessed 18 March 2015].

Freyman, M. and Salmon, R. **2013**. *Hydraulic fracturing and water stress: Growing competitive pressures for water*. *Ceres*. Boston, MA, USA. Retrieved from: http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers.

George, D. L. and Bowles., E. B. J. **2011**. Shale gas measurement and associated issues. *Pipeline and Gas Journal*, 238.

Hagon, S., Ottitsch, A., Convery, I., Herbert, A., Leafe, R., Robson, D. and Weatherall, A. **2013**. *Managing land for carbon: A guide for farmers, land managers and advisers Lake District National Park Authority and the University of Cumbria*. Kendal, UK. Retrieved from: http://www.lakedistrict.gov.uk/__data/assets/pdf_file/0008/345482/Managing-land-for-carbon-booklet.pdf.

HM Treasury. **2013**. *Autumn statement 2013*, The Crown, London, UK.

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

Hultman, N., Rebois, D., Scholten, M. and Ramig, C. **2011**. The greenhouse impact of unconventional gas for electricity generation. *Environmental Research Letters*, 6, 044008.

ISO. **2006a**. *EN ISO 14040: 2006 Environmental management - Life cycle assessment - Principles and framework*. International Organization for Standardization (ISO). Geneva, CH.

ISO. **2006b**. *EN ISO 14044:2006 Environmental management - Life Cycle assessment - Requirements and guidelines*. International Organization for Standardization (ISO). Geneva, CH.

Jiang, M., Griffin, W. M., Hendrickson, C., Jaramillo, P., VanBriesen, J. and Venkatesh, A. **2011**. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environmental Research Letters*, 6, 034014.

Kallmeyer, J. and Boetius, A. **2004**. Effects of temperature and pressure on sulfate reduction and anaerobic oixidation of methane in hydrothermal sediments of Guaymas Basin. *Applied and Environmental Microbiology*, 70, 1231-1233.

Karion, A., Sweeney, C., Petron, G., Frost, G., Michael Hardesty, R., 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. and Conley, S. **2013**. Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophysical Research Letters*, 40, 4393-4397.

New Energy Externalities Development For Sustainability. **2010**. *The NEEDS life cycle inventory database.* European Commission and DG Research: Porz, DE (July) Retrieved from: http://www.needs-project.org/needswebdb/index.php.

PE. **2012**. *GaBi Manual*. *PE International*. Stuttgart, DE. Retrieved from: http://www.gabi-software.com/fileadmin/GaBi_Manual/GaBi_6_manual.pdf.

Russell, C. and Hargreaves, T. R. **2013**. *Permit application: Irlam wells waste management plan*. *IGas Energy Plc*. Manchester, UK. Retrieved from: https://www.whatdotheyknow.com/request/205082/response/511630/attach/6/IRLM%20EPA%20008.pdf.

Shires, T. M., Loughran, C. J., Jones, S. and Hopkins, E. **2009**. *Compendium of greenhouse gas emissions methodologies for the oil and natural gas Industry*. *American Petroleum Institure (API)*. Retrieved from.

SONRIS. **2013**. *Well Information.* Strategic Online Natural Resources Information System (SONRIS): Baton Rouge, LA, USA (March 2014) Retrieved from: http://sonlite.dnr.state.la.us/sundown/cart_prod/cart_con_wellinfo1.

Stamford, L. and Azapagic, A. **2012**. Life cycle sustainability assessment of electricity options for the UK. *International Journal of Energy Research*, 36, 1263-1290.

Stamford, L. and Azapagic, A. **2014**. Life cycle environmental impacts of UK shale gas. *Applied Energy*, 134, 506 - 518.

Total S A. **2014**. *Regasification of LNG: Strategic access to markets* [Online] Paris, FR: Total S A. Available: http://www.total.com/en/energies-expertise/oil-gas/trading-shipping/fields-expertise/transportation-storage/regasification-lng-strategic-access-markets [Accessed July 2014].

UKOOG. **2013**. *UK Onshore Shale Gas Well Guidelines*. *UK Onshore Oil and Gas (UKOOG)*. London, UK. Retrieved from: http://www.ukoog.org.uk/onshore-extraction/industry-guidelines.

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

Williams, J., Field, L. and Lee, E. **2011**. *The impact of unconventional gas in Europe: A report to Ofgem*. *Poyry (for Ofgem)*. Warrington. Retrieved from: https://www.ofgem.gov.uk/ofgem-publications/38113/033publicreportunconventionalgasofgemlogov41.pdf.

Chapter 4. Economic viability of UK shale gas and potential impact on the energy market up to 2030

This paper has been submitted to the journal *Applied Energy* for publication and is currently under review.

This paper presents the life cycle costing of shale gas production and use to generate electricity. The impacts on the price of the 2030 gas mix and grid electricity are also presented. The introduction, tables and figures have been amended to fit into the structure of this thesis. The thesis author is the main author of the paper and is the one who collected the data used to calculate the life cycle cost of shale gas and shale gas electricity. The life cycle costs have been calculated by the thesis author, who also wrote the original manuscript. The co-authors are the supervisors of this PhD project and contributed to the paper by reviewing the original manuscript and giving input into what cost data to search for as well as guidance on how to go about calculating the life cycle cost of electricity.

Economic viability of UK shale gas and potential impact on the energy market up to 2030

Jasmin Cooper, Laurence Stamford and Adisa Azapagic*

School of Chemical Engineering and Analytical Science, The Mill, Room C16, Sackville Street, The University of Manchester, Manchester M13 9PL, UK

*Corresponding author: Adisa Azapagic

Phone: +44 (0)161 306 4363

Email: address: adisa.azapagic@manchester.ac.uk

Abstract

The UK is in the early stages of developing a shale gas industry and to date six test wells have been drilled but none yet exploited commercially. Some argue that shale gas could reduce energy prices and improve national energy security. However, the costs of bringing commercial-size wells into operation are uncertain and the impact shale gas could have on the UK energy market is unknown. Therefore, this chapter evaluates the economic viability of developing a UK shale gas industry and the impacts it could have on the UK gas and electricity markets and consumer energy bills up to 2030. The estimated life cycle (levelised) costs of shale gas production range from 0.13-15.76 pence/kWh, with an average value of 1.29 pence/kWh. The break-even price at which shale gas can be sold varies between 0.26-31.79 pence/kWh, averaging at 2.63 pence/kWh. The latter is two times higher than imported liquefied natural gas, around 30% more expensive than UK conventional gas and three times greater than the price of US shale gas. Electricity from shale gas is on average 17% more expensive than from conventional gas but still more competitive than most other electricity options, including coal and renewables. However, the impact of shale gas on the energy market would be limited to the expected range of penetration into the gas and electricity mixes, suggesting that it would have little effect on energy prices. This is reflected in an almost negligible impact on consumer energy bills. The potential of shale gas to boost the UK economy is also limited, contributing 0.017-0.033% to the (2015) GDP. This is an order of magnitude lower than the contribution of US shale gas to their GDP (0.2%), indicating that the economic success of shale gas in the US may not be replicated in the UK.

Keywords: shale gas; life cycle costs; electricity; energy costs

1. Introduction

This study sets out to estimate the costs of producing shale gas in the UK and the implications it could have for electricity prices and for the UK economy. Taking a life cycle approach, the costs of producing shale gas and generating electricity from it are estimated, alongside the effects on gas and electricity prices up to the year 2030. The estimated costs are compared to alternative sources of electricity, including other fossil fuel options, renewables and nuclear power. Previous studies considered different cost aspects of shale gas. Amion (2014) and Lewis et al. (2014) have estimated the cost of developing a shale gas industry (capital and operating costs) in the UK while BNEF (2013) have estimated the cost of producing shale gas in the UK. Elsewhere, cash flow analysis and net present value have been used to appraise the economic feasibility of shale gas production in Canada (Chen et al., 2015), Continental Europe (Weijermars, 2013) and Mexico (Weijermars et al., 2017). As far as the author is aware, this is the first study to integrate different aspects and to estimate the full life cycle cost (LCC) of shale gas from 'cradle to grave'. It is also the first study to consider the potential future effects of shale gas on the UK economy and household energy bills. A summary of the costs and other related aspects considered in this study in comparison to the literature can be found in Table 24.

Table 24 Shale gas costs and other related aspects considered in this study and the literature.

Economic aspect	This study	Literature
Capital and operating costs of shale gas production	✓	✓[a]
Well costs	✓	✓[b]
Wholesale/break-even price of shale gas	✓	✓[c]
Community charter costs	✓	✓[d]
Life cycle costs of shale gas from cradle to grave	✓	X
Employment per well/pad	✓	✓[e]
Operator and tax revenue	✓	X
Contribution to gross domestic product (GDP)	✓	X
Payback period	✓	X
Indirect economic impacts	✓	✓[f]
Life cycle cost of electricity from shale gas	✓	X
Cost of a gas mix which includes shale gas	✓	X
Cost of an electricity mix which includes shale gas	✓	X

[a] Amion (2014); BNEF (2013); Lewis et al. (2014); Taylor and Lewis (2013).
[b] Amion (2014).
[c] Taylor and Lewis (2013).
[d] Cronin (2013); UKOOG (2013); Taylor and Lewis (2013); Lewis et al. (2014).
[e] Taylor and Lewis (2013).
[f] Lewis et al. (2014).

2. Methodology

The method for estimating the LCC of shale gas production and electricity generation is detailed in the next sections, together with the data and key assumptions. Prior to that, the goal and scope of the study are defined below.

2.1. Goal and scope of the study

The main goals of this study are:

- to estimate the LCC of UK shale gas, considering its production and utilisation for electricity generation;
- to compare the LCC costs of shale gas to other electricity sources;
- to estimate the potential impact of shale gas on gas and electricity costs and on the UK energy market; and
- to investigate the potential impact of shale gas on the national economy.

The study considers the present situation and a medium-term future up to the year 2030.

All relevant life cycle stages from ‘cradle to grave’ are included, as shown in Figure 22. These comprise site exploration, drilling and hydraulic fracturing, shale gas extraction, treatment and distribution, well decommissioning and electricity generation; power plant construction and decommissioning are also considered. The LCC are estimated per kWh of shale gas produced and per kWh of electricity generated.

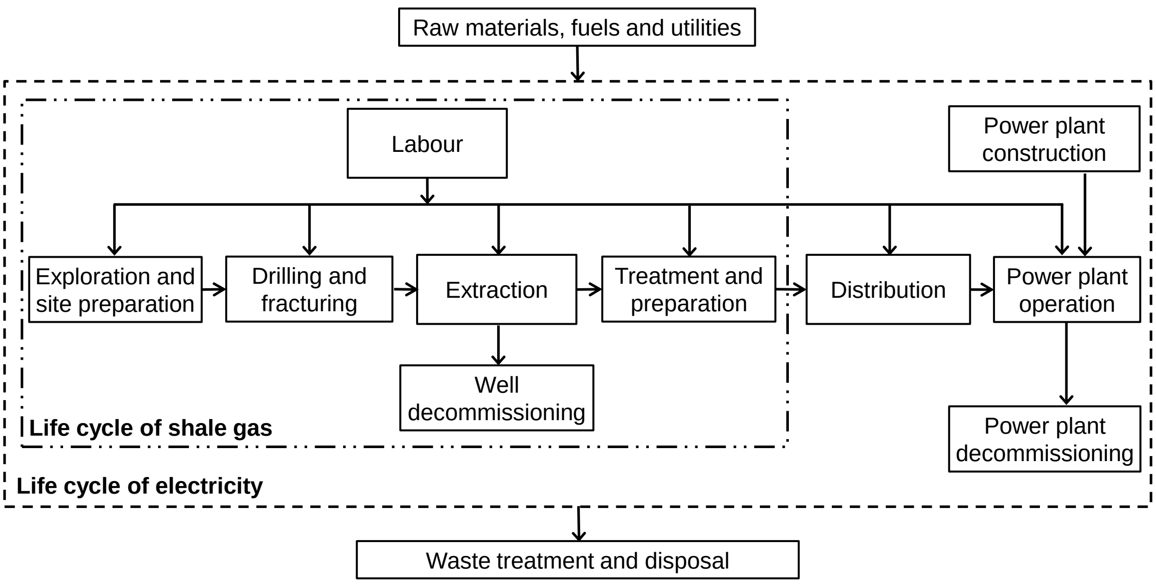


Figure 22: Life cycle stages considered in the estimation of life cycle costs of shale gas production and electricity generation.

2.2. Calculation of life cycle costs

This section first outlines the methodology used to estimate the costs of shale gas production, followed by the costs of electricity generation.

2.2.1. Cost of shale gas production

The total costs of shale gas production over the lifetime of a well have been estimated as follows:

$$LCC_{SG}=\frac{\sum_{n=1}^{N} C_{SG,n}}{E_{SG}}\times 10^{2} \qquad \text{(pence/kWh)} \qquad (1)$$

where:

LCC_{SG}	life cycle costs of shale gas (pence/kWh)
$C_{SG,n}$	total costs of shale gas production in year n (£)
E_{SG}	energy content of shale gas produced over the lifetime of the well (kWh)
n	year n (year)
N	lifetime of the shale gas well (years).

The total cost of producing shale gas in year n ($C_{SG,n}$) is equal to the sum of capital, operating, maintenance and labour costs in that year:

$$C_{SG,\,n}=CC_{SG,\,n}+COM_{SG,n}+CL_{SG,n} \qquad \text{(£/year)} \qquad (2)$$

where:

$CC_{SG,n}$	capital cost of producing shale gas in year n (£/year)
$COM_{SG,n}$	operating and maintenance costs of shale gas production in year n (£/year)
$CL_{SG,n}$	labour costs in year n (£year).

The energy content of shale gas (E_{SG}) produced over the lifetime of the well has been calculated using the estimated ultimate recovery (EUR) of gas over the lifetime of the well and the lower heating value (LHV) of shale gas:

$$E_{SG}= EUR \times LHV \qquad \text{(kWh)} \qquad (3)$$

where:

EUR estimated ultimate recovery of shale gas over the lifetime of the well (m^3)[1]

LHV lower heating value of shale gas (40.82 MJ/m^3 = 11.3 kWh/m^3).

The EUR has been calculated using the same method as in Chapter 3 (see Section BIV in Appendix B for details). Therefore, combining equations (1)-(3), the total life cycle costs of shale gas production are equal to:

$$LCC_{SG}=\frac{\sum_{n=1}^{N} C_{SG,n}}{E_{SG}}=\frac{\sum_{n=1}^{N} (CC_{SG,n}+COM_{SG,n}+CL_{SG,n})}{EUR \times LHV} \times 10^2 \quad \text{(pence/kWh)} \qquad (4)$$

The price at which shale gas can be sold at will be affected by different market factors, including costs of production (LCC), tax and time value of money, which in turn will affect its economic feasibility. The latter has been evaluated by estimating the net present value (NPV) of the total expected cash flow and revenue to the shale gas producer. These have been used to estimate the price at which shale gas can be sold, together with the associated tax earnings for the Government and the related contribution to the economy. A discounted cash flow analysis has been used for these purposes with the NPV calculated according to the following equation (Towler and Sinnot, 2008):

$$NPV_{SG}= \sum_{n=1}^{N} \frac{(NE_{SG,n}+D_{SG,n}-C_{SG,n})}{(1+i)^n} \quad (£) \qquad (5)$$

where:

NPV_{SG} net present value of total expected value of shale gas production (£)

$NE_{SG,n}$ net earnings from shale gas in year *n* after tax (£/year)

$D_{SG,n}$ depreciation in year *n* (£/year)

i discount rate (-).

The net earnings ($NE_{SG,n}$) in year *n* have been estimated based on the gross revenue from shale gas and depreciation in that year, taking into account the current tax rate on shale gas of 30% (HM Treasury, 2013):

$$NE_{SG,n}=(R_{SG,n}-D_{SG,n})\times(1-t_r) \quad \text{(£/year)} \qquad (6)$$

where:

$R_{SG,n}$ gross revenue from shale gas in year *n* (£/year)

$D_{SG,n}$ depreciation in year *n* (£/year)

[1] All references to the volume of gas are for the standard temperature and pressure, expressed as Nm^3 (normal cubic metres). For simplicity, "N" is not used in the notation.

t_r tax rate (0.3).

The gross revenue ($R_{SG,n}$) in year n is equal to the volume of gas produced in year n, multiplied by the LHV and the price at which the gas is sold in that year:

$$R_{SG,n}=V_{SG,n}\times LHV\times p \qquad (£/\text{year}) \qquad (7)$$

where:

$V_{SG,n}$ volume of shale gas produced in year n (m^3/year)

p unit price at which gas is sold (pence/kWh).

The value of p at which the NPV_{SG} is equal to zero is the break-even gas price and has been used to assess the competiveness of shale gas in the gas market. The above equations have also been applied to determine conditions for which shale gas production would be profitable.

The depreciation ($D_{SG,n}$) in year n is equal to:

$$D_{SG,n}=d_n\times t_d \qquad (£/\text{year}) \qquad (8)$$

where:

d_n the depreciable basis in year n (value of assets minus salvage value) (£/year)

t_d depreciation tax allowance rate (0.025).

2.2.2. Costs of electricity generation

The life cycle costs of electricity generation, also known as levelised electricity costs, have been calculated as follows (DECC, 2013a):

$$LCC_E=\frac{NPV_{EC}}{NPV_{EG}}\times 10^2 \qquad (\text{pence/kWh}) \qquad (9)$$

where:

LCC_E life cycle costs of electricity generation (pence/kWh)

NPV_{EC} net present value of total expected costs of electricity generation (£)

NPV_{EG} net present value of expected electricity generation over the lifetime of the plant (kWh).

The NVP of the total expected costs of electricity generation is equal to:

$$NPV_{EC}=\sum_{k=1}^{K}\frac{\left(CC_{E,\,k}+COM_{E,k}+CF_{E,k}+CCO_{2_k}\right)}{(1+r)^k} \qquad (£) \qquad (10)$$

where:

$CC_{E,k}$ capital cost of the power plant in year k (£/year)

$COM_{E,k}$ operating and maintenance costs (including labour costs) of electricity generation in year k (£/year)

$CF_{E,k}$ cost of fuel used for electricity generation in year k (£/year)

CCO_{2k} cost to the power plant of emitting CO_2 in year k (£/year)

r discount rate (-)

k year k

K lifetime of the power plant (years).

The cost of shale gas used as a fuel in the power plant has been estimated based on the price (*p*) at which production is profitable, calculated according to equations (4)-(8). This price has been varied through a sensitivity analysis to determine a range of profitable conditions.

The NPV of expected electricity generation over the lifetime of the plant has been calculated as:

$$NPV_{EG}=\sum_{k=1}^{K}\frac{E_k}{(1+r)^k} \qquad (£) \qquad (11)$$

where:

E_k net electricity generation in year k (kWh/yr).

Thus, merging equations (9)-(11), the total LCC or levelised costs of electricity generation is equal to:

$$LCC_E=\sum_{k=1}^{K}\left(\frac{CC_{E,\,k}+COM_{E,k}+C_{EF,k}+CCO_{2_k}}{E_k}\right)\times 10^2 \qquad \text{(pence/kWh)} \qquad (12)$$

2.3. Data and assumptions

2.3.1. Shale gas production

The costs of bringing a shale gas well into operation and maintaining its production are given in Table 25 and Table C1 in Appendix C; they comprise the following:

- capital: cost of equipment and materials needed to bring a shale gas well into operation, including the costs of:
    - seismic testing to determine the site geology;
    - pre-licencing and enabling, including planning and consent;
    - exploration and appraisal to determine if a well is viable;
    - drilling and completion;
    - hydraulic fracturing;
    - water and waste transport, storage and disposal;
    - decommissioning of the well, including cement plugging and end-of-life and after-life monitoring;
    - initial lump-sum payment to host communities, known as the *community charter*, which is compulsory in the UK (Cronin, 2013);
    - other costs, such as pad preparation, security, etc.;
- operating and maintenance (O&M): cost of equipment and materials needed to maintain the well during production and annual payments to host communities as part of the community charter, amounting to 1% of the annual revenue from the sales of shale gas; and
- labour: wages paid to employees involved in the life cycle of a shale well, from pre-development to decommissioning.

The EURs estimated in the previous chapter (10, 122 and 1,260 Mm^3) have been considered to determine the expected ranges of LCC_{SG} and p. The assumed production lifespan of a well is 30 years (Smil, 2015) and two years of pre-development activity to bring it into operation is also required (DECC, 2013b; House of Lords, 2014). The discount rate has been assumed at 10% (i = 0.1) which is the minimum acceptable rate of return for natural gas projects (Duman, 2012; Moniz et al., 2011). The depreciation tax allowance is

2.5% (t_d = 0.025) and Government tax 30% (t_r = 0.3) (HM Treasury, 2013). The depreciable basis d_n in year n is assumed to be equal to the expenditure in that year.

The NPV has been used to determine the payback period for shale gas projects as well as the effect of gas prices on the profitability. The latter is explored through a sensitivity analysis by calculating the NPV for a fixed discount rate of 10% for a range of gas prices (selected arbitrarily to cover a reasonably broad region). The influence of different discount rates on the results is also explored in the sensitivity analysis, by calculating the break-even price required at different discount rates, as well as how the latter affects fuel costs to the power plant. The internal rate of return (IRR) has not been considered in this work. The IRR would be the discount rate at which the NPV is equal to zero at the end of the well's lifespan for a specified gas price. As one of the aims of this work is to calculate the price of producing shale gas, the IRR has not been considered, but the effect of discount rate on gas prices has been assessed.

The estimated break-even prices have been assumed equal to the wholesale market prices to allow comparison with other gas options (conventional gas and liquefied natural gas (LNG)) and enable the estimation of fuel costs to the power plant. These assumptions have been made due to a lack of data on additional charges for shale gas entering the gas market (e.g. charges by gas traders, analysts, etc.) and the price it would be traded at, as well as the profit margins of shale gas operators. In reality, market prices will be higher than the break-even values.

One well producing only methane has been assumed, with natural gas liquids not considered. The latter has proven to be an important contributor to the overall economic viability of wells in the USA, as heavier hydrocarbons are more valuable (FT, 2016). However, without information on the type and volume of gas liquids found in UK shale plays, it is not possible to speculate on the amount that may be produced. Mineral royalties would also be charged, but this is charged on the tax paid (portion of taxable income taxed at a lower rate) and can be subject to relief under tax treaties (Deloitte, 2013; HM Revenues and Customs, 2011). As it is uncertain what tax treaties and lower tax rates would be applied (if any), mineral royalties are not included in the NPV analysis.

When considering the economic impact to the UK as a whole, the number of wells considered is 4,000 (Lewis et al., 2014). These wells are assumed to be drilled over a period of 15 years with a maximum drilling rate of 400 wells per year (Lewis et al., 2014). When considering impacts to local communities, drilling sites are considered. A drilling site (also referred to as a well site) is made up of well pads. A well pad is a vertical well (parent well) from which horizontal wells branch from. It is assumed each parent well will have four horizontal wells and each drilling site will have ten parent wells- 40 wells per site. The LCC calculations are for a horizontal well only.

This work estimates the cost of producing shale gas through the use of a cash flow analysis as well as the effect of discount rates on the profitability of shale gas projects. Due to the limitation on cost data (e.g. mineral royalties, landowner rent, shale gas operator profit margins and gas trader fees) the values calculated are estimations of the cost of producing shale gas in the UK and as a result the values are not completely representative of the full cost of production or the market price. Also the values listed in Table 25 represent the average cost of producing shale gas. As a well is part of a well site and will share a parent well with three other wells, the actual cost will vary.

Table 25: Costs of shale gas production (Amion, 2014; Cronin, 2013; Lewis et al., 2014; Taylor and Lewis, 2013).

Cost category	**Description**	**Cost per well (M£)**
Capital		
Seismic testing	3D imaging to determine geological characteristics	0.02
Pre-licensing and enabling	Preparation to secure site (planning permission, etc.)	0.01
Exploration and appraisal	Well exploration and testing	1.50
Drilling and completion	Equipment, materials, etc.	2.07
Hydraulic fracturing	Equipment, materials, etc.	5.14
Storage and transportation	Waste and water transportation and storage	0.32
Waste disposal	Waste management and treatment	0.69
Decommissioning	Plugging and other end-of-life activities	0.28
Community charter[a]	Initial lump-sum payment to hosting communities	2.50×10^{-3}
Other	Pad preparation, security, gas collecting and processing, equipment, pipelines and road access	0.13
Operation and maintenance[b]	Operation and maintenance	1.50
Labour	Staffing	6.30

[a] Total payment per well site is £100,000. Assuming that well sites contains 40 shale gas wells (Lewis et al., 2014), the payment per well amounts to £2,500.
[b] Excludes 1% cost paid to host communities as part of the community charter as it is a function of the revenue generated annually and calculated as part of operating and maintenance costs, $COM_{SG,n}$ in equation (4).

2.3.2. Electricity generation

The power plant data are summarised in Table 26 and Table 27. It is assumed that shale gas is used in a combined cycle gas turbine (CCGT) power plant, the prevalent gas technology in the UK (BEIS, 2016b) and parasitic energy consumption in the power plant has not been considered. The cost of shale gas to the power plant (CF_E) has been calculated based on the price (p) it can be sold at, estimated from equations (5)-(8), plus additional costs, such as gas distribution, value added tax (VAT) and the climate change levy (Table 28). Shale gas is assumed to be sold at its break-even price, because of the uncertainty and a lack of data on profit margins for shale gas production. It is also assumed that power plants buy their fuel directly from shale gas companies, using the National Grid for distribution to the power plant. These are conservative assumptions as gas would probably not be sold at the break-even price and the additional costs to the power plant may be affected by many different factors, including carbon price and any Government incentives. Furthermore, the power plant will more likely buy gas through gas traders than directly from the shale gas operator. However, in the absence of actual data, these assumptions are deemed reasonable, particularly as a wide range of prices and costs are considered in the sensitivity analysis.

The lifetime of the power plants has been assumed at 25 years (Parsons Brinckerhoff, 2013) and the discount rate at 10% (r = 0.1) (DECC, 2013a). Note that shale gas costs and annual electricity generation have been fixed for the lifetime of the power plant as is common in estimations of the LCC of electricity (DECC, 2013a; Parsons Brinckerhoff, 2013; Mott MacDonald, 2010).

Table 26: Specification of the CCGT power plant[a] (Mott MacDonald, 2010; Parsons Brinckerhoff, 2013).

Variable	**Value**
Installed capacity (MW)	900
Capacity factor (-)	0.928
Plant efficiency (%)	53
Low heating value of gas (kWh/m^3)	11.3
Net power generation (TWh/yr)	7.32
CO_2 emissions (g/kWh)	347[b]

[a] Due to a lack of data on future CCGT specifications, the same CCGT specification has been used for current and 2030 estimates.
[b] Based on the emission of 184 g CO_2/kWh of gas when combusted and the efficiency of CCGT of 53%.

Table 27: Costs of CCGT power plants[a] (Mott MacDonald, 2010; Parsons Brinckerhoff, 2013).

Cost category	**Low**	**Medium**	**High**
Capital (M£)	454	541	636
Operation and maintenance (£/MW·yr)			
Fixed[b]	26,000	31,000	36,000
Variable[b]	0[c]	651	1,220
CO_2 (£/t)	0[d]	54.30	135

[a] Due to a lack of data for future CCGT costs, the same costs have been assumed for the current and 2030 estimates.
[b] Fixed costs: labour, materials and equipment. Variable costs: repairs.
[c] No overhauls or equipment/components replacements.
[d] No costs charged for CO_2 emissions.

Table 28: Various costs to the operator of power plants (HM Revenues and Customs, 2016b; HM Revenues and Customs, 2016a; National Grid, 2016).

Cost category	**Value**
Transmission and distribution	0.0951 pence/kWh
Value added tax (VAT)	20% of the price of gas paid by the operator
Climate change levy	0.195 pence/kWh

2.3.3. Future gas and electricity scenarios

As mentioned in Section 2.1, in addition to estimating the LCC of shale gas electricity, a medium-term future up to 2030 is also considered in this work. The assumed UK gas mix in 2030 is shown in Table 29, together with the range of gas prices. These values have been used to estimate the cost of gas to the power plant, CF_E, relative to their contribution to the gas mix. These estimated values are assumed to represent the wholesale fuel prices and have been used to calculate the LCC_E of electricity generated from the 2030 gas mix. Following on from the previous chapter, two scenarios are considered for the future mix (Table 29) 'low' refers to a minimum and 'high' to a maximum expected production of shale gas in 2030, assuming all shale gas produced is used domestically.

The 2030 electricity mix can be found in Table 30**,** alongside the LCC of different electricity options and their contribution to the mix which have been used to estimate the LCC of electricity in 2030. The LCC costs have then been used to estimate the cost of electricity to the consumer (wholesale, excluding tax and other costs) assuming an average annual domestic consumption of 3,200 kWh per household (Villalobos, 2013). As indicated in

Table 30, three scenarios for electricity generation have been considered (DECC, 2013c): 'best', which assumes a high penetration of renewable electricity and a large drop in coal generation; 'worst', with a lower penetration of renewables and a higher contribution from coal; and 'central', representing an intermediate of the two scenarios. It is also assumed that the CCGT power plant will have the same capacity and efficiency in 2030 as the current technology (see Table 26) due to a lack of data on future developments of CCGT technology. However, as CCGT is a well-established technology, this is deemed a reasonable assumption.

Table 29: Assumed gas prices and contribution of different sources to the gas mix in 2030.

Gas source	Gas price (pence/kWh)			Gas production (bn m^3) (Contribution to the gas mix (%))	
	Low	*Medium*	*High*	*Low*[b]	*High*[b]
European pipeline import[a]	1.61	1.99	2.38	43 (48.9)	43 (48.9)
LNG import[a]	1.66	1.97	2.19	25 (28.4)	4 (4.5)
UK North Sea[a]	1.42	1.76	2.00	16 (18.2)	16 (18.2)
UK shale gas[c]	-	-	-	4 (4.5)	25 (28.4)

[a] Sources: FERC (2017), ICIS (2013), ICIS (2014), Statistics Norway (2017).
[b] Low and high: minimum and maximum expected production of shale gas by 2030, respectively (Williams et al., 2011).
[c] Calculated as part of this work (Section 3.1).

Table 30: Assumed life cycle (levelised) costs and electricity generation by source in 2030.

Electricity source	Cost (pence/kWh)[a]	Electricity generation (TWh/yr) (Contribution to the grid (%))		
		Best [b]	*Central* [s]	*Worst* [b]
Coal	13.85	1.86 (0.49)	1.86 (0.49)	4.20 (1.12)
Gas	- [c]	87.10 (22.77)	84.50 (22.37)	77.50 (20.67)
CCS	12.35	32.70 (8.55)	33.30 (8.82)	33.90 (9.04)
Nuclear	7.70	101.90 (26.64)	102.00 (27.01)	101.80 (27.15)
Renewables (average)[d]	10.53	159.00 (41.55)	156.00 (41.31)	157.50 (42.02)
Total	-	*382.56 (100)*	*377.66 (100)*	*374.90 (100)*

[a] Sources: BEIS (2016c), DECC (2013a).
[b] Best: high penetration of renewables and low contribution from coal; worst: lower penetration of renewables and a bigger contribution from coal; central: an intermediate case between 'best' and 'worst' (DECC, 2013c).
[c] Calculated as part of this work (Section 3.5.2.1).
[d] Solar PV: 6.70 pence/kWh; wind: 9.73 pence/kWh; biomass (woodchips): 11.75 pence/kWh; hydropower: 14.60 pence/kWh (BEIS, 2016c; DECC, 2013a) .

3. Results and discussion

3.1. Life cycle costs of shale gas

Based on the data in Table 25, it would cost £17.96 million to bring a single well into operation and maintain production over 30 years. The capital and labour costs make up the majority (92%) of the total cost. Half of the capital costs, estimated at £10.16 million, are due to hydraulic fracturing, which in turn is largely due to equipment (83%); for a detailed breakdown of costs, see Table C1 in Appendix C. By comparison, hydraulic fracturing equipment in the US makes up only 35% of capital costs (Bonakdarpour et al., 2011). The reason for the higher cost in the UK is because of the need to import technology (high power portable blenders and high power fracturing pumps) and expertise from the US.

The labour costs, estimated at £6.3 million over the whole life cycle of the well, contribute 35% to the total cost. Although the total number of jobs per (vertical) well over its lifetime is relatively small (17.5, of which four jobs are for pre-development, 13 for pad preparation and 0.5 for production, estimated using data from AMEC (2013) and Lewis et al. (2014)), the labour costs are high because of the high salaries in the oil and gas sector. On average, oil and gas workers earn between £36,000 and £160,000 per year, which is 34% to six times above the UK national average (Lewis et al., 2014; ONS, 2013). Also, the jobs created during the production stage are long term, which contributes to the high labour costs.

The remaining 8% is due to the operating and maintenance costs (£1.5 million). However, this excludes the payment of 1% of the revenue from shale gas as part of the community charter, as noted in Table 25. Based on the average EUR and the NPV estimated, this cost to the operator ranges between £351,000 to £665,000 per well, increasing the total operating and maintenance costs to up to £2.16 million and the total costs per well to up to £18.63 million. The payments to host communities as a result of the community charter projected by UKOOG (2013) are in the region of £125,000 to £250,000 per well; up to 64% lower than the estimates in this study. This difference is largely due to the different EURs assumed, with UKOOG using the values from Taylor and Lewis (2013) which are lower than the EURs in this study as they were based on data from US shale plays producing both gas and oil. The data in this study exclude oil production because the UK Bowland-Hodder shale play is expected to produce only natural gas. Furthermore, UKOOG did not state the gas prices they used so it is not possible to compare the results more closely.

Based on the above well costs and equations (1)-(4), the estimated life cycle costs of shale gas production (LCC_{SG}) range from 0.13-15.76 pence/kWh with the value of 1.29 pence/kWh for the average EUR (Table 31). These are compared in the next section to the prices (p) at which shale gas can be sold, estimated through the NPV analysis.

Table 31: Estimated life cycle costs and the break-even prices of shale gas at 10% discount rate.

Cost category	**Shale gas costs (pence/kWh)**		
	Low[a]	*Average*[a]	*High*[a]
Life cycle costs of shale gas (LCC_{SG})	0.13	1.29	15.76
Break-even price of shale gas (p)	0.26	2.63	31.79

[a] Low: high EUR; high: low EUR; average: average EUR.

3.2. Net present value and break-even price of shale gas

As explained in Section 2.2.1, the economic feasibility of shale gas production has been evaluated using a discounted cash flow analysis to estimate the NPV and break-even price of shale gas (equations (5)-(8)). The results are summarised in Figure 23, assuming a discount rate of 10%. The former indicates that the minimum (wholesale) price (*p*) at which shale gas can be sold at to break-even must exceed 2.63 pence/kWh for the average EUR but the break-even point (point in time when operator makes back initial investment and is no longer considered to be in debt) only occurs at the end of the well's lifetime. For the high and low EURs, the break-even prices are 0.26 and 31.79 pence/kWh, respectively (Table 31).

At higher prices, the break-even point is achieved sooner and the exploitation becomes profitable. For example, at 2.70 pence/kWh, the well breaks even in year 19 with the total NPV of £300,000 at the end of 30 years; at 3 pence/kWh, the NPV increases more than five-fold on the previous value (to £1.68 million) and the project breaks even in year ten (Figure 23). If the gas can be sold at 5 pence/kWh, the project is profitable in year three and the NPV increases to £10.89 million.

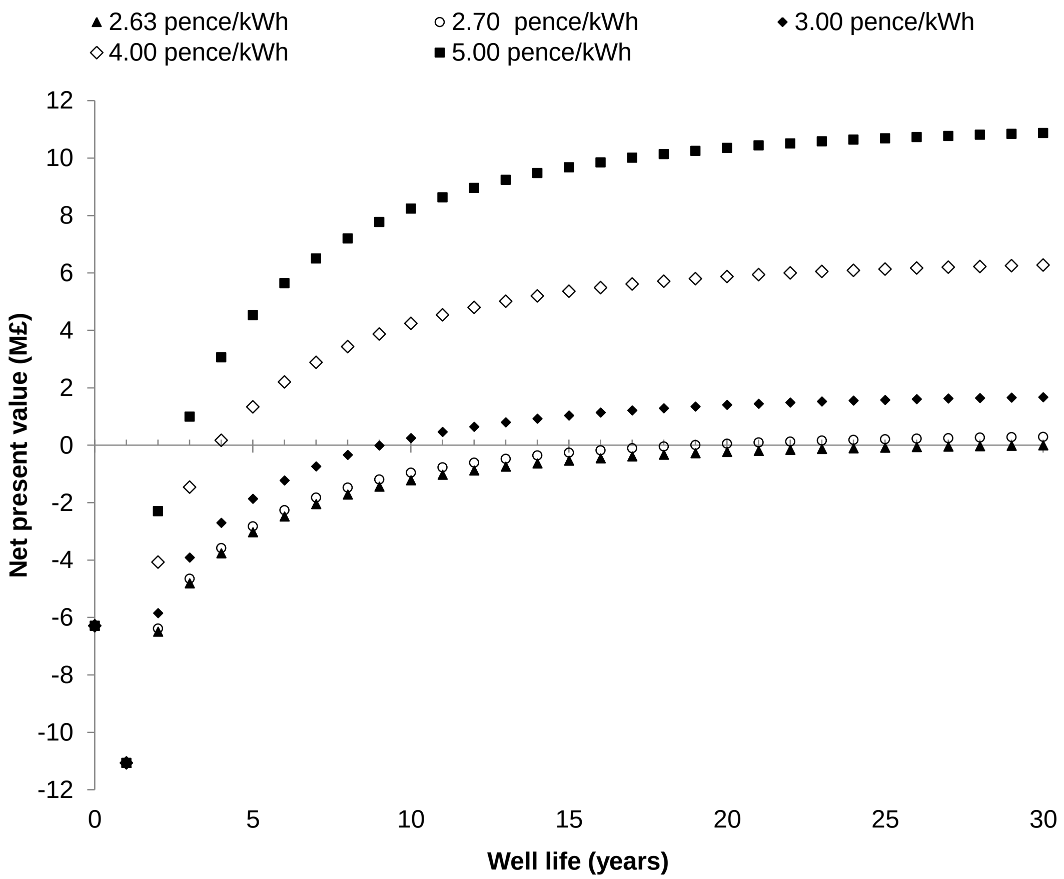


Figure 23: Net present values for different break-even gas prices over the lifetime of a well at 10% discount rate and the average EUR.

The estimated break-even prices for shale gas at the discount of 10% are compared in Figure 24 to the market prices of conventional gas and LNG in the UK and elsewhere. As can be seen, the average break-even price is almost 50% higher than the price of gas traded in the UK Heren NBP and around twice the price of LNG imports (mainly from Qatar). The price is also higher than any other gas considered here; the only exception is LNG from Japan, which is around 20% more expensive. In comparison to the break-even price of US shale gas, UK shale gas is 2.5 times more expensive, but the value for the former is estimated at a 15% discount. Assuming the same rate for UK shale gas, it becomes even more expensive (3.13 vs 1.09 pence/kWh for US shale gas). These results suggest that UK shale gas is not competitive with either domestic conventional gas or imports and is unlikely it will help to reduce energy prices in the UK.

However, as indicated in Figure 25, the break-even price of shale gas is sensitive to the discount rate assumed, ranging from 1.72 pence/kWh for 1% to 4.60 pence/kWh for 30%. At 2%, its price would be comparable to that of conventional gas traded at UK Heren NBP (1.82 vs 1.81 pence/kWh) and at 3% shale gas would be cheaper than UK North Sea gas. To match the trade price in the National Grid (1.76 pence/kWh), the discount rate would need to be reduced to 1.3% which, at the time of writing, is close to the UK's prime lending rate of 1.5% (Trading Economics, 2017). However, as shale gas is a new industry, it is considered a high risk venture (Crooks, 2016; Weng and Hefley, 2016). Therefore, it is highly unlikely that projects will be financed at such low rates. Finally, if a zero discount rate is assumed, shale gas would become competitive with LNG in Europe (see Figure 25). The above values refer to the average EUR; for the break-even prices for the low and high EURs, see Table C3 in Appendix C.

As far as the author is aware, only one previous study estimated break-even prices of UK shale gas (BNEF, 2013), with the values ranging from 1.55-2.66 pence/kWh for a 15% discount rate. These values are 18% to two times lower than the estimate in this study for the same discount rate (3.13 pence/kWh). However, the BNEF study did not consider the community charter, labour and decommissioning costs. It also assumed the capital cost in the range of £5 million to £7 million, which is lower than in this and other studies (Amion, 2014; Lewis et al., 2014; Taylor and Lewis, 2013).

It should be borne in mind that all estimates of shale gas prices and economic viability are uncertain, as they are based on the assumed rather than actual EUR values, which are currently unknown. However, a wide range of EUR values have been considered in this work, spanning very low to very high values. Furthermore, the viability of shale gas will also depend on the price at which gas is traded in the National Grid and the price power plants pay for gas (for the latter, see Section 3.4), which are all influenced by demand. In recent years, natural gas consumption in power plants has increased as generation from coal has decreased (BEIS, 2016d). Nevertheless, the estimates suggest that shale gas cannot compete with conventional gas and LNG, except at low discount rates.

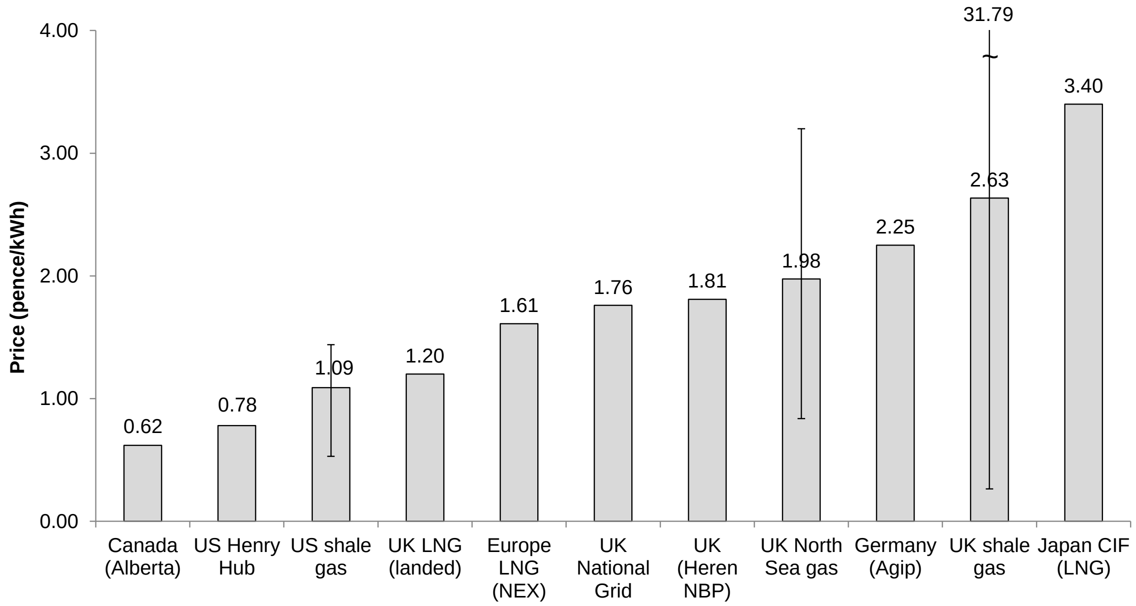


Figure 24: Comparison of shale and market gas prices.

[Shale gas: break-even price estimated in this work at 10% discount rate. The error bars represent high prices estimated at low EUR and vice versa. The values for US shale gas and UK North Sea gas are the break-even prices at 15% discount rate; the values for UK North Sea gas are for new projects (BNEF, 2013; Moniz et al., 2011; Oil & Gas UK, 2010; Weijermars, 2013; Wexelstein, 2014; Berman and Pittinger, 2011). UK LNG (landed), Germany (Agip) and Japan CIF (LNG) are average prices; all others are spot market prices (BP, 2014; BP, 2016; ICIS, 2014; Oil & Gas UK, 2010; Wexelstein, 2014; FERC, 2017). CIF: Cost, insurance and freight.]

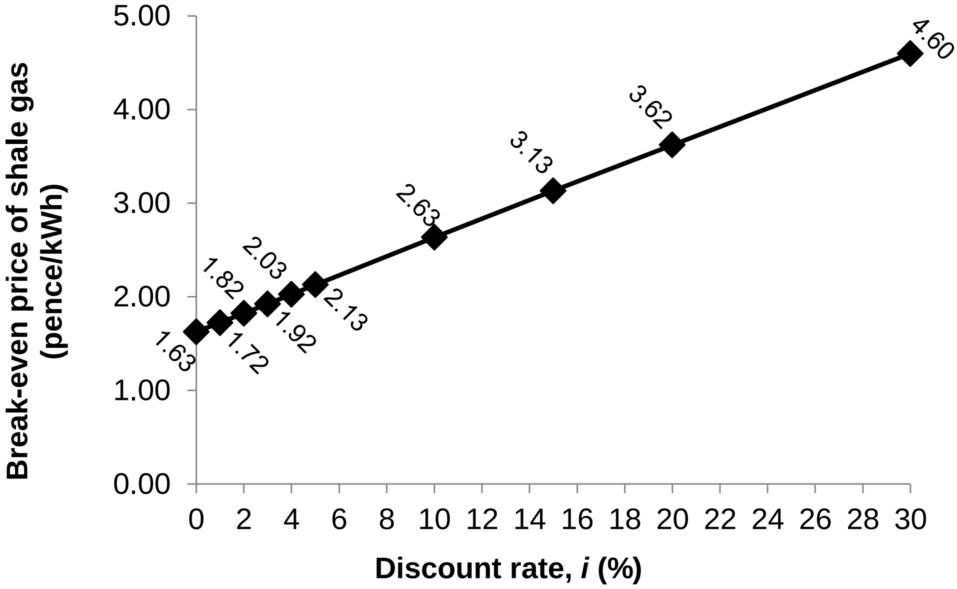


Figure 25: Break-even prices of shale gas for different discount rates at the average EUR.

3.3. Economic impacts of shale gas

In this section, the direct economic impacts of shale gas are discussed first, including operator's profit and the overall potential contribution to the economy. This is followed by potential indirect impacts on other industrial sectors.

3.3.1. Direct economic impacts

The estimated economic impact of a shale gas well on operator's profit and tax revenue to the Government is shown in Table 32 for different gas prices. As can be seen, for the gas prices considered in Figure 23, the operator's revenue ranges from £35 million to £66.5 million per well over its lifetime. Based on these values, the payments to host communities as part of the community charter would range from £351,000 to £665,000 (as mentioned in Section 3.1). In addition to this, the well would be contributing £10.5 million to £20 million in tax revenue. Assuming that 4,000 shale gas wells are drilled in the UK (Lewis et al., 2014), this could cumulatively generate £42 billion to £80 billion in tax income for the Government.

On an annual basis, the average operator's profit and tax revenue to the Government would be equivalent to £1.17 million to £2.22 million and £0.35 million to £0.67 million, respectively. It is predicted that up to 400 wells might be drilled per year during peak activity (Lewis et al., 2014). Based on this, shale gas could generate up to £468 million to £888 million in pre-tax annual profits for shale gas companies, contributing £328 million to £622 million annually (0.017-0.033%) to the GDP of £1,872 billion in 2015 (Statista, 2017). For context, the whole UK's oil and gas industry contributed £24 billion to the GDP in 2013 (BIS, 2015). Thus, this contribution of shale gas represents 1.4-2.6% of the total sector's GDP contribution.

The operator's revenue during peak production would also generate £141 million to £266 million in annual tax revenue (based on the annual profits in Table 32 and 400 wells drilled annually). Again for context, tax revenue in the UK in 2015 totalled £670 billion (Office for Budget Responsibility, 2016) so that the total contribution of shale gas to tax is equivalent to 0.02-0.04%. By comparison, shale gas in the US generated US$29 billion in revenue for companies in 2010, contributing 0.2% to the GDP and US$10 billion in tax revenue (0.07% of GDP) (Fullenbaum et al., 2011; The World Bank, 2017). Therefore, the economic effect of shale gas on the UK economy would be significantly lower.

This can partly be explained by the fact that the scale of production is likely to be smaller in the UK than in the US. The scale of production can be measured by the well density, which is defined as the number of horizontal wells per area available for exploration and extraction. As mentioned earlier, it is estimated that 4,000 horizontal wells will be drilled in the UK covering the area of 37,000 square miles, which gives a well density of 0.11 wells per square mile (Andrews, 2013; Lewis et al., 2014). In the US, the well density ranges from two to 11 wells per square mile, averaging at eight wells per square mile (EIA, 2011). Therefore, the scale and density of production in the UK would need to be much larger than currently envisaged to approach an impact on a national scale that is comparable to that in the US.

Table 32: Economic impacts of a shale gas well over its lifetime for different break-even gas prices at 10% discount rate and average EUR.

Gas price (pence/kWh)	Payback period (years)	Operator's revenue before tax (M£)	Community charter[a] (M£)	Tax, at 30% (M£)
2.63[b]	30	35.06	0.35	10.52
2.70	19	35.93	0.36	10.78
3.00	10	39.92	0.40	11.98
4.00	4	53.23	0.53	15.97
5.00	3	66.54	0.67	19.96

[a] 1% of revenue.
[b] Break-even price at 10% discount rate. Other values were arbitrarily chosen for the NVP calculations (see the previous section).

3.3.2. Indirect economic impacts

In addition to the direct impact on the UK economy discussed in the previous section, shale gas could have various indirect economic effects. Some of these would be on the sand and chemical sectors due to the significant amounts used for hydraulic fracturing (see Table C2 in Appendix C). It is estimated that some 9 Mt of sand will be required over the time required to hydraulically fracture 4,000 horizontal wells (15 years), which averages at around 600,000 t/yr (Lewis et al., 2014). To put this into context, in 2012 the UK consumed 26 Mt of sand for glass making, metals casting, construction, etc. (Bide et al., 2014). Thus, the average yearly sand requirement for shale gas extraction corresponds to around 2.3% of 2012 consumption. Based on the values in Table 25 and Table C1, shale gas could generate £2 billion in revenue for sand producers across the 4,000 wells or £200 million per year during peak activity, equivalent to 0.3% of the sand industry's annual income of £60.3 billion in 2012 (Bide et al., 2014).

Chemicals used to enhance the performance of the fracturing fluid (e.g. friction reducers, stabilisers, biocides, etc.) typically make up around 0.1% vol. of the fluid (Cuadrilla Resources, 2017); for details, see Table C2 in Appendix C. It is estimated that the use of chemicals for shale gas extraction in the UK could be worth £187,000 per horizontal well or £748 million for 4,000 wells (Lewis et al., 2014). This would contribute 0.2% annually to the total UK chemicals industry's turnover, reported at £42.97 billion in 2010 (ONS, 2010).

Therefore, shale gas development is unlikely to help boost the chemicals and sand industries. Despite this, there could be an increase in employment in these two sectors to meet the increase in demand for sand and chemicals.

3.4. Life cycle costs of electricity from shale gas

The life cycle costs of electricity (LCC_E) generated from shale gas depends, among others, on the cost of shale gas (CF_E) to the power plant, which in turn depends on the discount rate and the EUR. As can be seen in Table 33, the LCC_E estimated using equation (9), ranges from 2.02-132.25 pence/kWh for the discount rates of 5-30%. For the medium CCGT costs and average EUR, the LCC_E varies from 8.42-14.04 pence/kWh. For the low CCGT costs and high EUR, the LCC_E is significantly lower (2.02-2.56 pence/kWh), while for the high CCGT costs and low EUR, it is much higher (64.78-132.25 pence/kWh).

These estimates are compared to the LCC_E of other sources of electricity in Figure 26 for the 10% discount rate. At low costs (see Table 33 for details) shale gas electricity is significantly cheaper than the other electricity options considered. However, for the medium conditions, shale gas electricity is 17% more expensive than conventional gas (9.59 vs 8 pence/kWh). Nevertheless, it is still more competitive than most other electricity options, except for nuclear power which has costs similar to conventional gas. However, in the worst case, the LCC_E is ten times higher than conventional gas and almost five times greater than the costs of the most expensive option, solar PV.

At a discount rate of 5% and assuming medium LCC_E (8.42 pence/kWh), electricity from shale gas is comparable to conventional gas and nuclear power and it is cheaper than coal and all the renewables considered here (see Table 33 and Figure 26). Figure 26 also shows that the LCC of shale gas electricity is mostly influenced by fuel costs. As indicated in Table 33, fuel costs contribute 50-61% to the total for the low costs, 63-78% for the medium and 91-95% for the high. By comparison, fuel costs for conventional gas and LNG electricity contribute around 60% to the total, which is comparable to the lower range (62%) for the medium costs of shale gas electricity. Therefore, these results suggest that shale gas electricity could be competitive with other electricity options in terms of life cycle costs. However, this is highly dependent on the fuel cost to the power plant, which is in turn dependent on the discount rate and the EUR.

Table 33: Life cycle (levelised) cost of shale gas electricity for different shale gas prices and power plant costs.

Cost category (pence/kWh)	**Power plant costs and EUR**[a]	**Discount rate (fuel)**				
		5%	*10%*	*15%*	*20%*	*30%*
Capital	Low	0.68	0.68	0.68	0.68	0.68
	Medium	0.81	0.81	0.81	0.81	0.81
	High	0.96	0.96	0.96	0.96	0.96
Operating & maintenance	Low	0.32	0.32	0.32	0.32	0.32
	Medium	0.39	0.39	0.39	0.39	0.39
	High	0.46	0.46	0.46	0.46	0.46
Fuel[b]	Low	1.02	1.13	1.24	1.35	1.56
	Medium	5.34	6.51	7.64	8.75	10.96
	High	58.67	72.52	86.09	99.46	126.14
CO_2	Low	0	0	0	0	0
	Medium	1.88	1.88	1.88	1.88	1.88
	High	4.69	4.69	4.69	4.69	4.69
Total life cycle cost (LCC_E)	**Low**	**2.02**	**2.13**	**2.24**	**2.35**	**2.56**
	Medium	**8.42**	**9.59**	**10.72**	**11.83**	**14.04**
	High	**64.78**	**78.63**	**92.20**	**105.57**	**132.25**

[a] "Low": low power plant costs (Table 27) and high EUR (1260 Mm^3); "Medium": medium power plant costs (Table 27) and average EUR (122 Mm^3); "High": high power plant costs (Table 27) and low EUR (10 Mm^3).
[b] Cost of shale gas to the power plant, calculated by summing up the break-even (assumed as wholesale) shale gas prices (see Table C3 in Appendix C) and the additional costs to the power plant, discounted over time (Table 28).

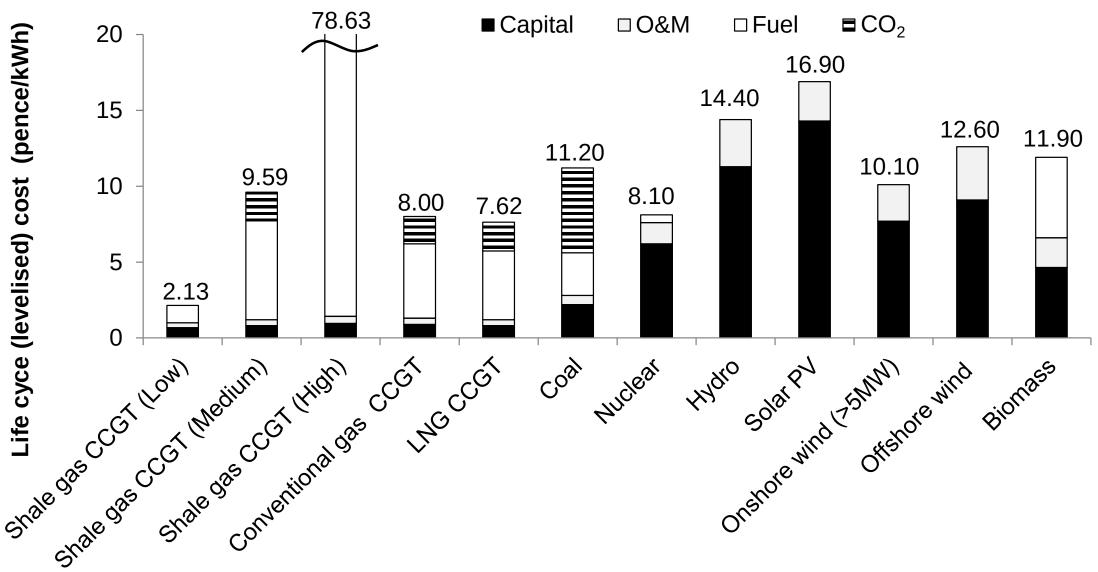


Figure 26: Comparison of the life cycle (levelised) costs of shale gas electricity with other (present) electricity sources in the UK.

[Shale gas: low - high EUR and low power plant costs; medium - average EUR and medium power plant costs; high - low EUR and high power plant costs; discount rate: 10%; for details see Table 33. Costs for other technologies estimated based on data from DECC (2012a) and IRENA (2012). O&M: operating and maintenance costs. CCGT: combined cycle gas turbine; LNG: liquefied natural gas.]

3.5. Scenario analysis

3.5.1. Cost of gas in 2030

The costs of gas to the power plant in 2030 have been estimated using the same method as for the current costs (see Section 2.3.2), based on the prices of different gas sources and their contribution to the gas mix given in Table 29. The results in Figure 27 suggest that for the high penetration of shale gas (28.4% in the gas mix), the gas cost would be around 7% higher than for the low penetration (4.5% in the gas mix). This is due to shale gas being more expensive than gas imports and UK North Sea gas (see Table 29).

When no shale gas in the mix is considered, the cost of gas is similar to that for low shale gas penetration (2.66 vs 2.62 pence/kWh, respectively). In the case of high penetration, the average cost would be 8% higher than without it. However, as can be seen in Figure 27, there is a great variation in the values, so the cost could be up to six times higher in the worst case and up to 30% lower in the best case. To validate the results, the estimated cost without shale gas is compared to that reported in the literature (Figure 27) showing good agreement. The relative difference of 7% is due to differing gas mixes and prices, the latter of which were modelled in the literature (BEIS, 2016a) based on the current and projected conditions of the European gas market while the current study used UK market data. The effect of the level of penetration of shale gas on the cost of generating gas electricity is discussed in the next section.

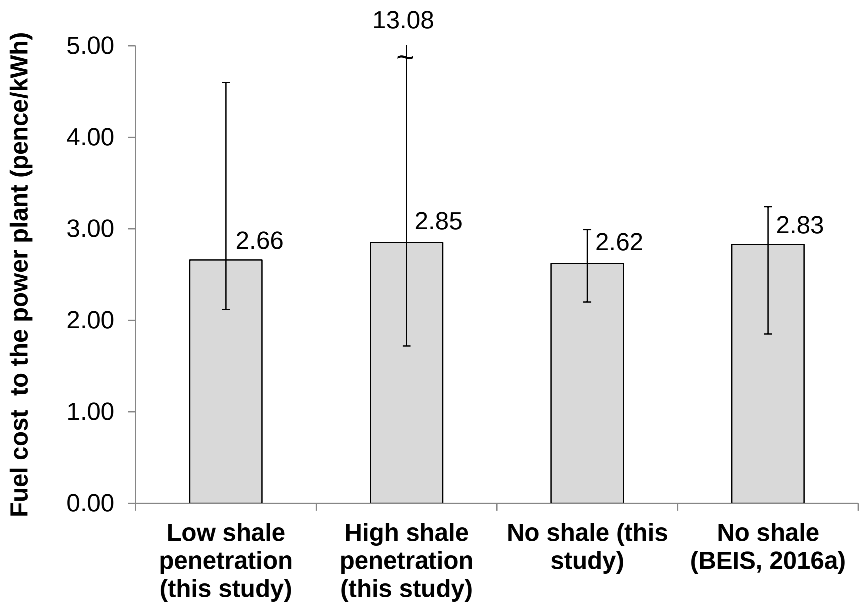


Figure 27: Costs of fuel to power plants (CF_E) in 2030 for low and high shale gas penetration in comparison with no shale gas in the mix.

[The break-even price of shale gas at 10% discount rate (Table 31) has been used along with the prices of the other gas options (Table 29) to calculate the cost of the gas mix in 2030 based on their contribution to the mix. This value has then been used to estimate the gas costs to the power plant by adding the additional costs listed in Table 28.]

3.5.2. Costs of electricity in 2030

3.5.2.1. Costs of electricity from gas

The estimated costs of gas to the power plant discussed in the previous section have been used to calculate the life cycle (levelised) cost of electricity generated from the assumed 2030 gas mix using equation (9). As can be seen in Figure 28, there is only a small difference (4%) in the average cost of electricity between the low and high penetration mixes (8.10 vs 8.46 pence/kWh, respectively). Following the trends from the previous section, the high penetration mix has higher LCC_E. These costs are also similar to the average costs without shale gas in the mix (8.03 pence/kWh). Thus, the impact of shale gas on the costs of future gas electricity would be insignificant. The only exception to this is for the worst case high shale scenario, for which the cost is more than double the highest cost of electricity without shale gas.

The average estimated cost with no shale gas is 5-10% lower than that reported in the literature; see Figure 28. It can also be noticed from the figure that the literature estimates without shale slightly exceed or are similar to the values estimated here for both low and high penetration of shale gas. This is due to at least two factors: different assumptions in the studies and the small effect of shale gas on the costs of electricity generation (1.7-12%; shale gas contributes 4.5-28.4% to the gas mix and fuel costs make up 63-78% of the LCC_E).

Compared to the present average cost of 5.80 pence/kWh (DECC, 2012a), the 2030 costs estimated in this study are around 30% higher. A similar increase in costs is also reported by DECC (2012a) and BEIS (2016a). This is largely due to the need to build an additional 26 GW of CCGT plants by 2030 (DECC, 2012b; BEIS, 2016b).

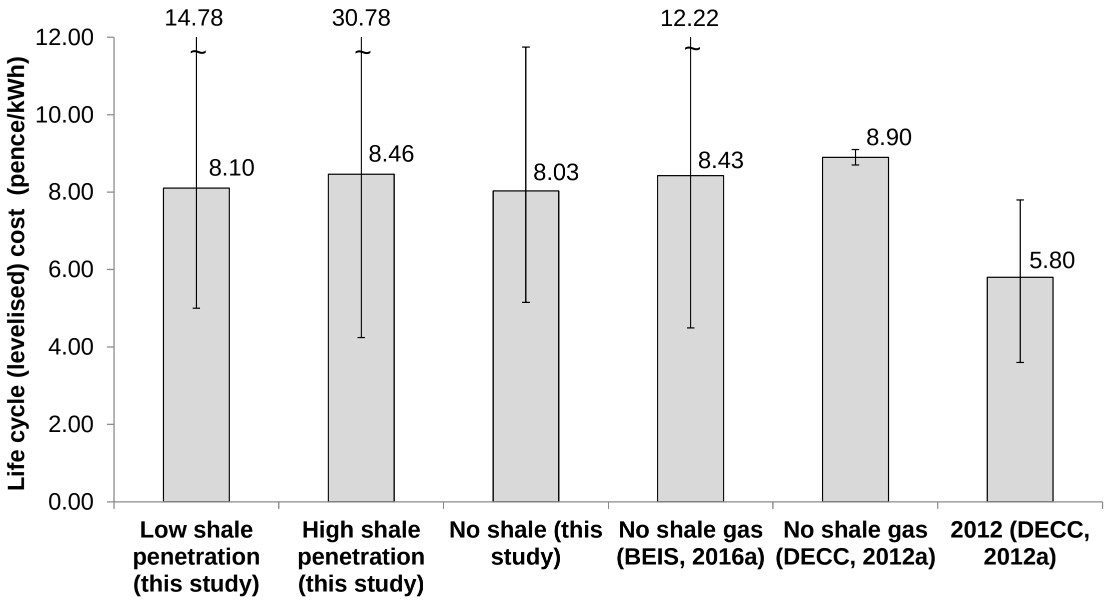


Figure 28: Estimated life cycle (levelised) costs of electricity *(LCC_E)* in 2030 for low and high penetration of shale gas in comparison with no shale gas in the mix.

[This study: The values on top of the bars represent costs for the average EUR and central power plant costs. Error bars correspond to low and high EUR of shale gas as well as low and high power plant costs. Literature: The values on top of the bars are average costs and the error bars correspond to low and high values.]

3.5.2.2. Costs of the electricity mix

Similar to the previous findings, the level of shale gas penetration into the electricity mix has little effect on the future cost of electricity. As shown in Figure 29 (and detailed in Table C4 in Appendix C), the LCC_E in the central case are estimated at 9.40-9.48 pence/kWh for the low and high penetrations of shale gas in 2030, respectively. Thus, the difference in costs between the two scenarios is almost indistinguishable, with the higher-shale mix being slightly more expensive. These costs are also quite close to those without shale gas in the mix, estimated at 9.38 pence/kWh, thus suggesting that shale gas will not influence the cost of the electricity mix under the conditions considered in this study. Also shown in Figure 29, the estimates of electricity costs without shale gas are slightly lower than those calculated from the literature data (9.47-9.71 pence/kWh) for comparison purposes. As before, the reason for this difference is different assumptions for various costs.

To determine the potential effect of shale gas on consumer electricity bills, Figure 29 also shows the estimated wholesale prices of electricity in 2030. It can be seen that the annual price of wholesale electricity increases by around 10%, from £281 in 2013 up to £310 in 2030. However, this increase is largely due to the predicted increase of low-carbon technologies and CCS in the electricity mix, despite the expectation that the costs of most renewables and nuclear power will decrease by 2030 (see Figure C1 in Appendix C).

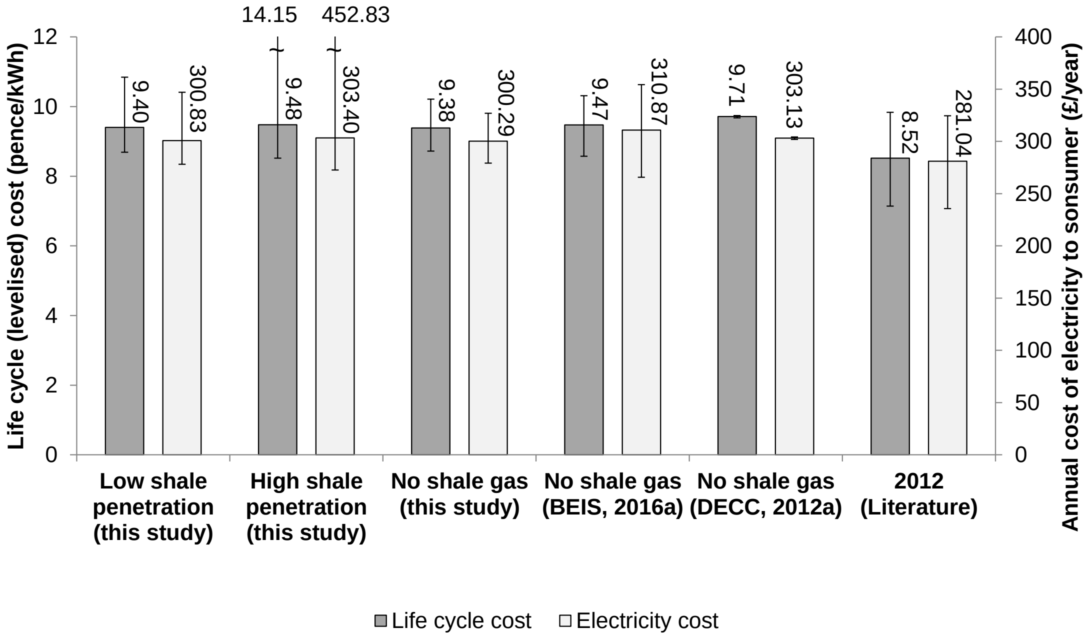


Figure 29: Estimated life cycle (levelised) and annual electricity costs to consumer in 2030 for low and high penetration of shale gas in comparison with no shale gas in the mix

[The values on top of the bars represent the average costs in the central case. This study: Error bars correspond to low and high costs of gas electricity (Figure 28) and worst and best electricity scenarios (see Table 30 for specifications of the central, best and worst scenarios). No shale gas (BEIS, 2016a; DECC, 2012a): Error bars correspond to low and high values. These have been estimated in this work using literature gas fuel costs in Figure 27 and cost of gas electricity in 2030 reported by DECC (2012a). 2012 (Literature): Data sourced from DECC (2012a); Ofgem (2013); DECC (2013c); British Gas (2016); EDF Energy (2016); eon (2016); npower (2016); ScottishPower (2017); SSE (2017). Cost to consumer estimated from LCC assuming annual consumption of 3200 kWh per household.]

4. Conclusions

This study has assessed the economic viability of UK shale gas and the impacts it could have on the UK gas and electricity markets, both at present and in the medium-term future, up to 2030. The life cycle costs are estimated to range from 0.13-15.76 pence/kWh, with an average value of 1.29 pence/kWh. The break-even price of shale gas ranges from 0.26-31.79 pence/kWh, averaging at 2.63 pence/kWh. This is more expensive than imported LNG (1.20 pence/kWh) and UK conventional gas (1.76-1.98 pence/kWh). It is also around three times more expensive than US shale gas.

The cost of producing shale gas is primarily dominated by capital (hydraulic fracturing) and labour costs. The majority of the hydraulic fracturing costs are for equipment because this will most likely have to be imported from the US. The labour costs are high, in spite of low job generation, because the average salary in the oil and gas industry is high and jobs in gas extraction are over a long period.

Shale gas costs are sensitive to three parameters: estimated ultimate recovery (EUR) and related volume of gas produced, discount rate and the price at which the gas is sold. The results suggest that shale gas is competitive with conventional gas and LNG at low discount rates (<3%). At discount rates below 10% and high overall gas production volume, the price of shale gas is much lower than the price of conventional North Sea gas, but is higher than US shale gas and market prices in other parts of the world. Despite this, under the circumstances at which shale gas could be profitable, £35 million to £67 million in revenue could be generated per well (£140 billion to £266 billion for 4,000 wells), as well as £11 million to £20 million in tax revenue (£42 billion to £80 billion for 4,000 wells). However, this would be a small boost to the UK economy, contributing 0.017-0.033% to the GDP. This is much lower than the contribution in the US (0.2%), indicating that the economic effect of shale gas on the UK economy would be significantly lower than in the US.

The LCC of shale gas electricity range from 2.02-132.25 pence/kWh, for the discount rates 5-30%, depending on the cost of the power plant and the EUR. For the medium power plant costs and average EUR, the LCC is 9.59 pence/kWh, which is 17% higher than electricity from conventional gas. Nevertheless, it is still more competitive than most other electricity options, except for nuclear power which has similar costs to conventional gas. In the worst case, however, the LCC of shale gas electricity is ten times higher than conventional gas and almost five times greater than solar PV which is the most expensive alternative among the other options considered. However, the cost benefits of shale gas over other electricity options diminish as fuel costs increase.

The findings in this work also suggest that shale gas will have little effect on future (2030) gas and electricity costs, with high penetration of shale gas leading to slightly higher costs. The impact on future electricity bills would also be negligible, partly as a result of the expected increase of low-carbon technologies and CCS in the mix.

Nomenclature

$C_{SG,n}$	total costs of shale gas production in year *n* (£)
$CC_{E,k}$	capital cost of the power plant in year *k* (£/year)
$CC_{SG,n}$	capital cost of producing shale gas in year *n* (£/year)
CCO_{2k}	cost to the power plant of emitting CO_2 in year *k* (£/year)
$CF_{F,k}$	cost of fuel used for electricity generation in year *k* (£/year)
$CL_{E,k}$	labour costs in year k (£/year)
$CL_{SG,n}$	labour costs in year *n* (£/year)
$COM_{E,k}$	operating and maintenance costs of electricity generation in year *k* (£/year)
$COM_{SG,n}$	operating and maintenance costs of shale gas production in year *n* (£/year)
d_n	the depreciable basis in year *n* (value of assets minus salvage value) (£/year)
$D_{SG,n}$	depreciation in year *n* (£/year)
E_k	net electricity generation in year *k* (kWh/year)
E_{SG}	energy content in shale gas produced over the lifetime of the well (kWh)
EUR	estimated ultimate recovery of shale gas over the lifetime of the well (m^3)
i	discount rate (interest charged on loans) (-)
k	year *k*
K	lifetime of the power plant (years)
LCC_E	life cycle costs of electricity generation, also known as levelised electricity costs (pence/kWh)
LCC_{SG}	life cycle costs of shale gas (pence/kWh)
LHV	lower heating value of shale gas (kWh/m^3)
n	year *n* (year)
N	lifetime of the shale gas well (years)
$NE_{SG,n}$	net earnings from shale gas in year *n* after tax (£)
NPV_{EC}	net present value of total expected costs of electricity generation (£)
NPV_{EG}	net present value of expected electricity generation over the lifetime of the
NPV_{SG}	net present value of total expected costs of shale gas production (£)
	plant (kWh)
p	unit price at which gas is sold (£/kWh)
r	discount rate (interest charged on loans) (-)
$R_{SG,n}$	gross revenue from shale gas in year *n* (£/year)
t_d	depreciation tax allowance (-)
t_r	tax rate (-)
$V_{SG,n}$	volume of shale gas produced in year *n* (m^3/year)

References

AMEC. **2013**. *Strategic environmental assessment for further onshore oil and gas licensing*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/consultations/environmental-report-for-further-onshore-oil-and-gas-licensing.

Amion. **2014**. *Potential economic impacts of shale gas in the Ocean Gateway*. *IGas Energy plc and Peel Environment Ltd*. Liverpool, UK. Retrieved from: http://www.igasplc.com/media/10851/ocean-gateway-shale-gas-impact-study.pdf.

Andrews, I. J. **2013**. *The Carboniferous Bowland Shale gas study: geology and resource estimation*. *British Geological Society (BGS)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/226874/BGS_DECC_BowlandShaleGasReport_MAIN_REPORT.pdf.

BEIS. **2016a**. *BEIS 2016 Fossil Fuel Price Assumptions*. *Department for Business, Energy and Industrial Strategy (BEIS)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/576542/BEIS_2016_Fossil_Fuel_Price_Assumptions.pdf.

BEIS. **2016b**. *Digest of United Kingdom Energy Statistics 2016*. *Department for Business, energy and Industrial Strategy (BEIS)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/577712/DUKES_2016_FINAL.pdf.

BEIS. **2016c**. *Electricity generation costs*. *Department for Business, Energy and Industrial Strategy (BEIS)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/566567/BEIS_Electricity_Generation_Cost_Report.pdf.

BEIS. **2016d**. *UK Energy in Brief 2016*. *Department for Business, Energy and Industrial Strategy (BEIS)*. London, UK. Retrieved from: https://www.gov.uk/government/statistics/uk-energy-in-brief-2016.

Berman, A. E. and Pittinger, L. F. **2011**. US shale gas: less abundance, higher cost. [Online], 5 August. Available: http://www.theoildrum.com/node/8212 [Accessed: February 2017].

Bide, T., Brown, T. J., Hobbs, S. F. and Idoine, N. **2014**. *United Kingdom minerals year 2013*. *British Geological Survey (BGS)*. London. Retrieved from: https://www.bgs.ac.uk/downloads/start.cfm?id=2930.

BIS. **2015**. *Growth Dashboard*. June 2015. *gov.uk*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/396740/bis-15-4-growth-dashboard.pdf.

BNEF. **2013**. *The economic impact on UK energy policy of shale gas and oil*. April, 2014. *Bloomberg New Energy Finance (BNEF)*. London, UK. Retrieved from:

http://about.bnef.com/white-papers/the-economic-impact-on-uk-energy-policy-of-shale-gas/.

Bonakdarpour, M., Flanagan, B., Holling, C. and Larson, J. W. **2011**. *The economic and employment contributions of shale gas in the United States*. *IHS Global*. Washington DC. Retrieved from: http://energyindepth.org/wp-content/uploads/2011/12/Shale-Gas-Economic-Impact-Dec-2011_EMB1.pdf.

BP. **2014**. *BP statistical review of world energy June 2014*. *British Petroleum (BP)*. London, UK. Retrieved from: http://www.bp.com/content/dam/bp-country/de_de/PDFs/brochures/BP-statistical-review-of-world-energy-2014-full-report.pdf.

BP. **2016**. *BP Statistical Review of World Energy June 2016*. *British Petroleum (BP)*. London, UK. Retrieved from: https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf.

British Gas. **2016**. *Our fuel mix* [Online]. Available: http://www.britishgas.co.uk/business/about-us/fuel-mix [Accessed February 2017].

Chen, Z., Osadetz, K. G. and Chen, X. **2015**. Economic appraisal of shale gas resources, an example from the Horn River shale gas play, Canada. *Petroleum Science*, 12, 712-725.

Cronin, K. **2013**. *Community engagement charter oil and gas from unconventional reservoirs*. *UK Onshore Oil and Gas (UKOOG)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/256360/Publication_UKOOG_communityengagementcharterversion6.pdf.

Crooks, E. **2016**. Oil and gas: Debt fears flare up. *Financial Times*, 21 March 2016, Available from: https://www.ft.com/content/d48b1922-eadd-11e5-bb79-2303682345c8.

Cuadrilla Resources. **2017**. *Fracturing fluid* [Online] Preston, UK. Available: http://www.cuadrillaresources.com/what-we-do/hydraulic-fracturing/fracturing-fluid/ [Accessed 2017 February].

DECC. **2012a**. *Electricity generation costs*. *Department of Energy and Climate Change*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65713/6883-electricity-generation-costs.pdf.

DECC. **2012b**. *Gas Generation Strategy*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65654/7165-gas-generation-strategy.pdf.

DECC. **2013a**. *Electricity generation costs*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from:

https://www.gov.uk/government/publications/electricity-generation-costs-december-2013.

DECC. **2013b**. *Onshore oil and gas exploration in the UK: regulation and best practice*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/503067/Onshore_UK_oil_and_gas_exploration_England_Dec15.pdf.

DECC. **2013c**. *Updated energy and emissions projections 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/239937/uep_2013.pdf.

Deloitte. **2013**. *Oil and gas taxation in the UK: Deloitte taxation and investment guides*. *Deloitte*. London, UK. Retrieved from: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/dttl-er-UK-oilandgas-guide.pdf.

Duman, R. J. **2012**. *Economic viability of shale gas production in the Marcellus Shale; indicated by production rates, costs and current gas prices*. Masters thesis, Michigan Technological University.

EDF Energy. **2016**. *Our fuel mix EDF Energy* [Online]. Available: http://www.edfenergy.com/fuel-mix [Accessed February 2017].

EIA. **2011**. *Review of emerging resources: U.S. shale gas and shale oil Plays*. *US Energy Information Administration (EIA)*. Washington DC. Retrieved from: https://www.eia.gov/analysis/studies/usshalegas/pdf/usshaleplays.pdf.

eon. **2016**. *Fuel mix* [Online]: eon. Available: https://www.eonenergy.com/About-eon/Fuel-Mix [Accessed February 2017].

FERC. **2017**. 2017. *World LNG Estimated Landed Prices: Dec-16* [Online], Federal Energy Regulatory Commission (FERC), January 2017. Available from: https://www.ferc.gov/market-oversight/mkt-gas/overview/ngas-ovr-lng-wld-pr-est.pdf.

FT. **2016**. *Commodities* [Online] London, UK: Financial Times (FT). Available: http://markets.ft.com/research/markets/Commodities [Accessed February 2017].

Fullenbaum, R. F., Larson, J. W. and Dorsey, J. **2011**. *The economic and employment contributions of shale gas in the United States*. *IHS Global Insight (USA)*. Washington DC. Retrieved from: http://anga.us/media/content/F7D1750E-9C1E-E786-674372E5D5E98A40/files/shale-gas-economic-impact-dec-2011.pdf.

HM Revenues and Customs. **2011**. *Mineral Royalties Relief: Repeal*. *HM Revenues and Customs*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/192145/ots_mineral_royalties.pdf.

HM Revenues and Customs. **2016a**. *Climate change levy rates* [Online] London, UK: HM Revenues and Customs. Available: https://www.gov.uk/government/publications/rates-and-allowances-climate-change-levy/climate-change-levy-rates [Accessed February 2017].

HM Revenues and Customs. **2016b**. *VAT rates* [Online] London, UK: HM Revenues and Customs. Available: https://www.gov.uk/vat-rates [Accessed February 2017].

HM Treasury. **2013**. *Autumn statement 2013*, The Crown, London, UK.

House of Lords. **2014**. *The economic impact on UK energy policy of shale gas and oil*. May, 2014. *House of Lords: Economic Affairs Committee*. London, UK. Retrieved from: http://www.publications.parliament.uk/pa/ld201314/ldselect/ldeconaf/172/172.pdf.

ICIS. **2013**. *Heren European Spot Gas Market ICIS (Independent Chemical Information Service)*. London. Retrieved from: http://www.icis.com/energy/gas/europe/european-spot-gas-markets/.

ICIS. **2014**. *Heren LNG Markets Daily*. *ICIS (Independent Chemical Information Service)*. Retrieved from: http://www.icis.com/energy/liquefied-natural-gas/lng-daily-and-weekly-reports/.

IRENA. **2012**. *Hydropwer*. *International Renewable Energy Agency (IRENA)*. Abu dhabi, UAE. Retrieved from: http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf.

Lewis, C., Speirs, J. and MacSweeney, R. **2014**. *Getting ready for UK shale gas: Supply chain and skills requirements and opportunities*. *United Kingdon Onshore Oil and Gas and Ernst and Young*. London, UK. Retrieved from: http://www.ey.com/Publication/vwLUAssets/Getting_ready_for_UK_shale_gas/$FILE/EY-Getting-ready-for-UK-shale-gas-April-2014.pdf.

Moniz, E. J., Jacoby, H. d., Meggs, A. J. M., Armstrong, R. C., cohn, D. R., Connors, S. R., Deutch, J. M., Ejaz, Q. J., Hezir, J. S., Kaufman, G. M., Kenderdine, M. a., O'Sullivan, F., Paltsev, S., Parsons, J. E., Perez-Arriaga, I., Reilly, J. M., Seto, C., Webster, M. D., Yang, Y., McRae, G. S. and Ruppel, C. **2011**. *The future of natural gas: an interdisciplinary MIT study*. *Massachusetts Institute of Technology Energy Initiative (MITEI)*. Cambridge, MA, USA. Retrieved from: https://mitei.mit.edu/system/files/NaturalGas_Report.pdf.

Mott MacDonald. **2010**. *UK electricity generation costs update*. *Department of Energy and Climate Change (DECC)*. Brighton, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65716/71-uk-electricity-generation-costs-update-.pdf.

National Grid. **2016**. *The statement of gas transmission transportation charges*. *National Grid*. London, UK. Retrieved from: http://www2.nationalgrid.com/UK/Industry-information/System-charges/Gas-transmission/Charging-Statements/.

npower. **2016**. *Where our electricity comes from: Fuel mix* [Online] Houghton le Spring, UK. Available: http://www.npower.com/home/about-npower/our-responsibility/how-we-source-our-fuels/ [Accessed February 2017].

Office for Budget Responsibility. **2016**. *Economic and fiscal outlook*. *Office for Budget Responsibility*. London, UK. Retrieved from: http://budgetresponsibility.org.uk/efo/economic-fiscal-outlook-march-2016/.

Ofgem. **2013**. *Updated household energy bills explained Ofgem*. London, UK. Retrieved from: https://www.ofgem.gov.uk/ofgem-publications/64006/householdenergybillsexplainedudjuly2013web.pdf.

Oil & Gas UK. **2010**. *Economic Report 2010*. *Oil & Gas UK*. Aberdeen, UK. Retrieved from: http://oilandgasuk.co.uk/wp-content/uploads/2015/05/EC021.pdf.

ONS. **2010**. *Annual Business Inquiry, 2008 Revised Results* [Online]: Office for National Statistics (ONS). Available: http://webarchive.nationalarchives.gov.uk/20160105160709/http://www.ons.gov.uk/ons/rel/abs/annual-business-inquiry/index.html [Accessed February 2017].

ONS. **2013**. *Annual survey of hours and earning UK, 2013*. December 2013. *Office for National Statistics (ONS)*. London, UK. Retrieved from: http://www.ons.gov.uk/ons/rel/ashe/annual-survey-of-hours-and-earnings/2013-provisional-results/stb-ashe-statistical-bulletin-2013.html.

Parsons Brinckerhoff. **2013**. *Electricity generation cost model- 2013 update of non-renewable technoligies*. *Department of Energy and Climate Change (DECC)*. Manchester, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223634/2013_Update_of_Non-Renewable_Technologies_FINAL.pdf.

ScottishPower. **2017**. *Bill breakdown*. *ScottishPower*. Glasgow, UK. Retrieved from: http://www.scottishpower.co.uk/customer-services/bills-payments/billbreakdown/.

Smil, V. **2015**. *Natural gas: fuel for the 21st century*, First, Chinchester, UK: Wiley.

SSE. **2017**. *Energy legal and regulatory information* [Online] Perth, UK. Available: https://sse.co.uk/help/energy/energy-regulations#item1 [Accessed February 2017].

Statista. **2017**. *Gross domestic product at current market prices of the United Kingdom (UK) from 2000 to 2015 (in million GBP)* [Online] New York, NY, USA. Available: https://www.statista.com/statistics/281744/gdp-of-the-united-kingdom-uk-since-2000/ [Accessed January 2017].

Statistics Norway. **2017**. *External trade in goods* [Online] Oslo, NO: Statistics Norway. Available: https://www.ssb.no/statistikkbanken/SelectVarVal/Define.asp?subjectcode=01&Pro

ductId=01&MainTable=UhArOljeGass&SubTable=1&PLanguage=1&nvl=True&Qid=0&gruppe1=Hele&gruppe2=Europa2&gruppe3=Hele&aggreg2=NO&VS1=VareGruppeOljeGass&VS2=LandkoderEnkeltland&VS3=&mt=0&KortNavnWeb=muh&CMSSubjectArea=&StatVariant=&checked=true [Accessed February 2017].

Taylor, C. and Lewis, D. **2013**. *Getting shale gas working*. *Institute of Directors (IoD)*. London, UK. Retrieved from: www.iod.com/~/media/.../IoD_Getting_shale_gas_working_MAIN_REPORT.pdf.

The World Bank. **2017**. *Data* [Online] Washington DC. Available: http://data.worldbank.org/ [Accessed February 2017].

Towler, G. and Sinnot, R. **2008**. *Chemical engineering design: Principles, practice and economics of plant and process design*, London, UK: Elsevier.

Trading Economics. **2017**. *United Kingdom prime lending rates* [Online]: Trading Economics. Available: http://www.tradingeconomics.com/united-kingdom/bank-lending-rate [Accessed February 2017].

UKOOG, **2013**, *United Kingdom Onshore Oil and Gas launches shale community engagement charter* [Press release] London, UK: United Kingdom Onshore Oil and Gas (UKOOG). Available: http://www.ukoog.org.uk/about-ukoog/press-releases/58-united-kingdom-onshore-oil-and-gas-launches-shale-community-engagement-charter.

Villalobos, D. **2013**. *Review of typical domestic consumption values*. *Office of Gas and Electricity Markets (Ofgem)*. London, UK. Retrieved from: https://www.ofgem.gov.uk/sites/default/files/docs/2013/09/tdcv-review-consultation_0.pdf.

Weijermars, R. **2013**. Economic appraisal of shale gas plays in Continental Europe. *Applied Energy*, 106, 100-115.

Weijermars, R., Sorek, N., Sen, D. and Ayers, W. B. **2017**. Eagle Ford Shale play economics: U.S. versus Mexico. *Journal of Natural Gas Science and Engineering*, 38, 345-372.

Weng, Y. and Hefley, W. E. **2016**. *The global impact of unconventional shale gas development: economics, policy and interdependence*, First ed, Zug, Switzerland: Springer International.

Wexelstein, L. **2014**. 2014. *The North Sea: How does the UK compare?* [Online], January 2015. *Presentation*. Available from: https://www.woodmac.com/.

Williams, J., Field, L. and Lee, E. **2011**. *The impact of unconventional gas in Europe: A report to Ofgem*. *Poyry (for Ofgem)*. Warrington. Retrieved from: https://www.ofgem.gov.uk/ofgem-publications/38113/033publicreportunconventionalgasofgemlogov41.pdf.

Chapter 5. Social sustainability assessment of shale gas in the UK

This paper has been submitted to the journal *Sustainable Production and Consumption* for publication and is currently under review.

This paper presents the social sustainability assessment of shale gas extracted in the UK and its use to generate electricity, as well as its impact on the UK electricity mix. The introduction, tables and figures have been amended to fit into the structure of this thesis. The thesis author is the main author of the paper and is the one who collected the data needed for the various indicators. The results presented are those calculated by the thesis author, who also wrote the original manuscript. The co-authors are the supervisors of this PhD project and contributed towards the paper by reviewing the original manuscript and giving guidance during the selection of social sustainability indicators.

Social sustainability assessment of shale gas in the UK

Jasmin Cooper, Laurence Stamford, Adisa Azapagic*

School of Chemical Engineering and Analytical Science, The University of Manchester

The Mill, Room C16, Sackville Street, Manchester, M13 9PL, UK

*Corresponding author: adisa.azapagic@manchester.ac.uk

Abstract

The majority of shale gas studies so far have focused on environmental impacts with few considering societal aspects. This study assesses the social impacts of shale gas production and utilisation for electricity generation. The assessment has been carried out based on 14 indicators, addressing the following social sustainability issues: employment, health and safety, nuisance, public perceptions, local communities, infrastructure and resources. Shale gas is compared to a range of other electricity options, including other fossil fuel based electricity generation options, nuclear and renewables. Where appropriate and possible, the social impacts are evaluated on a life cycle basis. The results suggest that extraction and utilisation of shale gas would lead to a range of benefits, including employment opportunities and financial gains by local communities. However, these are limited and countered by a number of social barriers that need to be overcome, including low public support, noise, traffic, strain on infrastructure (e.g. wastewater treatment facilities), land use conflict and availability of regulatory resources. Furthermore, shale gas does not present a notable opportunity for increasing energy security, unless its production increases significantly above current predictions.

Keywords: shale gas; fracking; hydraulic fracturing; electricity; social sustainability

1. Introduction

This study evaluates the social impacts of shale gas production and utilisation for electricity generation in the UK and how it compares with other electricity sources. The social impacts are underexplored, with most studies so far based in the US (see Chapter 2 for details) and have considered issues such as employment, health and safety, nuisance, public perceptions, impact on local communities, infrastructure and resources. The most widely studied issues are employment, health and safety and public perceptions (refer to Section 4 in Chapter 2), while a handful of studies have considered nuisances, local community impacts and infrastructure and resources.

Studies on nuisances to humans and wildlife are related to traffic, noise and the presence of equipment. The increase in traffic due to shale gas development has been linked to increased road accidents (Graham et al., 2015) and emissions of nitrogen oxides and particulate matter (Goodman et al., 2016). Noise exposure near sites can have adverse effects on human hearing (Hays et al., 2016) and can affect animal behaviour (Barber et al., 2010; Barber et al., 2011). However, the presence of equipment does not appear to have adverse effects on local wildlife or biodiversity (Jones et al., 2014).

The impacts to local communities have been evaluated in the literature considering community benefits, such as charters, benefit agreements and compensation schemes to offset damages caused by activities related to development. Most authors argue that there is a need for compensation and insurance schemes against environmental damage caused by shale gas development (Behrer and Mauter, 2017; ter Mors et al., 2012; Wetherell and Evensen, 2016), as damage to the environment can affect the livelihoods of residents, such as ill-health and property value. The impacts on infrastructure and resources have been analysed based on the resources needed to bring a shale gas well into operation (Arredondo-Ramírez et al., 2016; Gao and You), as well as the handling of waste produced (wastewater in particular) and the effect on improving energy security (Adamus and Florkowski, 2016; Akob et al., 2016; Johnson and Boersma, 2013).

Therefore, the social impacts have been evaluated based on indicators which fall into the categories identified in Chapter 2 as well as those listed above. As far as the author is aware, this is the first study of its kind, also representing the most comprehensive assessment of the social sustainability of shale gas.

2. Methodology

In total, 14 indicators have been used to evaluate the social sustainability of shale gas; these are given in Table 34. They have been selected to cover the social issues identified in the literature discussed in the previous section and in Chapter 2, as well as to reflect

UK specific conditions (House of Lords, 2014). Hence, the following aspects have been used to derive indicators:

- employment;
- health and safety;
- nuisance;
- public perception;
- local communities; and
- infrastructure and resources.

In addition to evaluating the social sustainability, some of the indicators have been used to compare shale gas to the other electricity options in the UK electricity mix: conventional gas, liquefied natural gas (LNG), coal, nuclear power, hydroelectricity, solar PV, wind (offshore) and biomass. Based on the relevance and data availability, the comparison is only possible for the following four indicators: direct employment, worker injuries, public support and diversity of fuel supply. The basis for comparison is determined by the units in which these indicators are measured; for the first two, the comparison is per TWh electricity generated and for the rest, it is dimensionless (see Table 34).

The indicators and the methods for their calculation are detailed in the next section. The data and assumptions for the calculations for both shale gas and the other electricity technologies can be found in Appendix D.

Table 34: Indicators used to assess the social sustainability of shale gas.

Issue	**Indicator**	**Unit**
Employment	Direct employment[a]	person-years/TWh
	Local employment	%
	Gender equality	-
Health and safety	Worker injuries[a]	injuries/TWh
Nuisance	Noise	dB
	Traffic increase	%
Public perception	Public support[a]	%
	Media impact	-
Local communities	Spending on local suppliers	%
	Direct community investment	%
Infrastructure and resources	Diversity of fuel supply[a]	-
	Wastewater treatment	-
	Land use	-
	Regulatory staff requirements	-

[a] Used for comparison with the other electricity options.

2.1. Employment

2.1.1. Direct employment

This indicator measures the total number of jobs created directly due to shale gas production and utilisation. Calculated on a life cycle basis, it takes into account the number of jobs created along the supply chain, the duration of employment and the total amount of electricity generated over the lifetime of the power plant, based on the approach developed by Stamford and Azapagic (2012):

$$DE = \frac{\sum_i^I DE_i \times t_i}{P_{tot}} \quad \text{(person-years/TWh)} \qquad (13)$$

where:

DE total direct employment generated in the life cycle of shale gas electricity along the supply chain (person-years/kWh)

DE_i number of jobs created in life cycle stage *i* (no. of persons)

t_i duration of employment in life cycle stage *i* (years)

P_{tot} total amount of electricity generated over the lifetime of the power plant (TWh)

i life cycle stage (-)

I total number of life cycle stages (-).

Data for the estimation of this indicator can be found in tables D1 and D2 in Appendix D. The DE has been calculated as part of this work for shale gas, LNG and hydroelectricity; for the remaining technologies, the DE values have been sourced from Stamford and Azapagic (2012). Indirect employment related to associated activities, such as production of chemicals or equipment, is beyond the scope of the study and are not considered. Employment created directly from the development of shale gas is considered and indirect and induced jobs, such as chemicals manufacturing and regulatory resources are not included.

2.1.2. Local employment

The local employment indicator is used to measure contributions to the local economy and communities through the employment of local workforces during the extraction, production and utilisation of shale gas. It is defined as the percentage of new jobs created that could be filled by local workforces and is calculated as follows (Stamford and Azapagic, 2012):

$$P_{LE} = \frac{LE}{TE} \times 100 \quad (\%) \qquad (14)$$

where:

P_{LE} proportion of employees that could be hired from the local community (%)

LE number of employees that could be hired from the local community (persons-years/TWh)

TE total number of employees needed (persons-years/TWh).

For the data used to calculate local employment, see Table D3 in Appendix D.

2.1.3. Gender equality

Diversifying the workforce is important as the workforce in the gas sector is predominantly male (Oil and Gas UK, 2015). Therefore, the gender equality indicator aims to capture workforce diversity by measuring the ratio of male to female workers. A scale ranging from –1 to 1 has been used in this work, with –1 representing no female workers and 1 an entirely female workforce; 0 represents a 50:50 split of the genders, assumed as an ideal situation. This indicator is estimated according to the following equation and data in Table D4 in Appendix D:

$$GE = \frac{FW}{50} - 1 \qquad (-) \qquad (15)$$

where:

GE gender equality index (-)

FW percentage of female workforce (%).

2.2. Health and safety: worker injuries

This indicator measures workers' safety across the supply chain related to shale gas production and utilisation. Like direct employment, it is also estimated on a life cycle basis considering the total electricity generated over the lifetime of the power plant, injury rates and employment across the supply chain:

$$WI=\sum_i^I E_i r_i \qquad \text{(injuries/TWh)} \qquad (16)$$

where:

WI number of worker injuries (injuries/TWh)

E_i employment in life cycle stage *i* (person-years/TWh)

r_i annual injury rate in life cycle stage *i* (injuries/person-years).

Injuries included in the estimate are fatalities, major injuries and less serious injuries that cause an absence from work of more than three days; for the data, see tables D2 and D5 in Appendix D.

2.3. Nuisance

2.3.1. Noise

The potential impact of noise to local residents has been evaluated using literature data for noise expected during shale gas production (Arup, 2014a). These data are compared to recorded noise levels from the US and, for context, to the noise levels of other activities, such as traffic, music and conversation (Arup, 2014a; MDE and DNR, 2015; NIDCD, 2010; Vondra, 2014).

2.3.2. Traffic increase

An increase in road traffic heading towards well sites is expected due to the need to bring equipment, people and materials to and from sites. The expected increase in traffic volume on roads around well sites in the UK has been estimated based on the congestion reference flow (CRF). The CRF considers traffic characteristics and road types and is used as a measure of the likely increase in traffic congestion during peak (rush) hours. The CRF is calculated as follows (Standards for Highways, 1997; Standards for Highways, 1999):

$$CRF = CAP \times L \times W_f \times \frac{100}{PkF} \times \frac{100}{PkD} \times \frac{AADT}{AAWT} \quad \text{(vehicles/day)} \qquad (17)$$

where:

CRF	congestion reference flow (vehicles/day)
CAP	maximum vehicle capacity per road lane (vehicles/day)
L	number of lanes on the road (-)
W_f	width factor – width of road lanes relative to a standard width of 3.65 m (-)
PkF	proportion of daily traffic flow during peak hours (-)
PkD	the directional split of flow during peak hours (-)
AADT	the annual average daily traffic flow (vehicles/day)
AAWT	the annual average weekday flow (vehicles/day).

The CRF has been estimated for both urban and rural roads using literature data (Broderick et al., 2011); for details, see tables D6 and D7 in Appendix D. The CRF has only been calculated for well site development and does not include the traffic that would be incurred from wastewater removal from the site. This is because the volume of wastewater produced is highly variable and uncertain (see Section DVII.II in Appendix D) and transportation of wastewater can be affected by water management strategies, such as onsite storage, treatment and recycling. Wastewater transportation is discussed further in sections 2.6.2 and 3.6.2. Also, the activities that would be carried out (drilling, hydraulic fracturing) are intermittent resulting in changes to traffic volume being intermittent. However as equation (17) does not factor in traffic intermittency, it has not been considered.

2.4. Public perception

2.4.1. Public support

Previous studies have used surveys to assess what percentage of participants are ‘pro’, ‘unsure/neutral’ or ‘anti’ shale gas. While this information is useful, it does not allow for an overall evaluation of public support – or the lack of – for shale gas. Therefore, a single measure, termed ‘public support index’ (PSI), has been developed as part of this work. Using averaged data from various public perception surveys (Castell et al., 2014; DECC, 2014; O'Hara et al., 2015), the PSI is calculated as the difference between the percentage in support and in opposition for each electricity option. The ‘unsure/neutral’ responses are not considered. The PSI can range from –100% to 100%, where the former represents complete opposition and the latter complete support. The data for estimating the PSI can be found in Table D8 in Appendix D.

2.4.2. Media impact

The framing of shale gas in the media can influence people’s opinions, as discussed in Section 4.3 in Chapter 2. Therefore, it is important to measure the impact media may have on forming opinions about shale gas. For these purposes, a media impact index has been developed in this work as outlined below. The focus is on social media and specifically on the five most popular sites: Twitter, Facebook, LinkedIn, Google+ and YouTube (Small Business Trends, 2015; Social Media Today, 2015). Three stakeholder groups are considered, representing potential key opinion formers: shale gas operators, Government and research bodies and non-governmental organisations (NGOs). They span the full spectrum of attitudes towards shale gas, respectively from ‘pro’ through ‘unsure/neutral’ to ‘anti’; for details of the stakeholders considered; see Table D9 in Appendix D.

The media impact index indicates which stakeholder groups are more presented in social media, suggesting a greater influence on opinion forming. It is estimated as follows:

$$MI_s = \frac{P_s}{P_T} \qquad (-) \qquad (18)$$

where:

MI_s total media impact of stakeholder s (-)

P_S total presence of stakeholder s on all social media considered (-)

P_T total presence of all stakeholders on all social media considered (-).

The impact (MI_s), is measured on a scale from zero to one, with the latter representing complete dominance and prior no or minimal presence and impact.

The presence (P_s) of stakeholder s on each social media platform ($P_{s,j}$) is estimated taking into account their presence through different types of metrics (j) such as tweets, 'likes' and followers (see Table D9) according to:

$$P_{s,j} = \frac{n_{s,j}}{n_{j\,(max)}} \qquad (-) \qquad (19)$$

where:

$P_{s,j}$ presence of stakeholder s for type of metric j (-)

$n_{s,j}$ amount in metric type j (e.g. number of tweets, 'likes', etc.) by stakeholder s (-)

$n_{j\,(max)}$ the highest amount in metric type j (-)

j metric type (e.g. tweets, 'likes', etc.).

The presence P_S of each stakeholder across all social media platforms is then estimated as:

$$P_s = \sum_j^J P_{s,j} \qquad (-) \qquad (20)$$

where:

J total number of the types of social media metrics (-).

The total presence of all stakeholders on all the media P_T is equal to:

$$P_T = \sum_m^M P_s \qquad (21)$$

where:

m social media platform (-)

M total number of social media platforms (-).

The data used to calculate the media impact index can be found in Table D9 in Appendix D.

2.5. Local communities

2.5.1. Spending on local suppliers

The spending on supplies needed for shale gas presents an opportunity for the local economy and businesses. Thus, this indicator measures the proportion of total spending by operators on equipment, materials or services that will be sourced from local suppliers over 15 years, the time it takes for the shale gas industry to mature (Lewis et al., 2014). It is calculated as follows (Stamford and Azapagic, 2012):

$$P_{LS}=\frac{S_{LS}}{S_T}\times 100 \qquad (\%) \qquad (22)$$

where:

P_{LS} percentage of total spending on local suppliers (%)

S_{LS} total spending on local suppliers (£)

S_T total expenditure (£).

The data for estimating P_{LS} can be found in Table D10 in Appendix D.

2.5.2. Direct community investment

This indicator measures investments in and donations to local communities by operators across the shale gas electricity supply chain through various schemes to offset damages caused by activities related to shale gas development. In the UK, these include the community charter and the shale gas wealth fund (Cronin, 2013; HM Treasury, 2016; Oil and Gas UK, 2015; UKOOG, 2013) and is estimated as a percentage of the operator's total annual revenue (Stamford and Azapagic, 2012):

$$P_{LI}=\frac{LI}{R_T}\times 100 \qquad (\%) \qquad (23)$$

where:

P_{LI} percentage of direct investment into the local community (%)

LI annual investment in and donations to the local community (£/year)

R_T total annual revenue (£/year).

Further details on the estimation of this indicator can be found in Table D11 in Appendix D.

2.6. Infrastructure and resources

2.6.1. Diversity of fuel supply

The diversity of fuel supply (DFS) is a measure of national energy security – the more diverse the fuel supply, the greater the energy security by reducing dependency on any one fuel or supplier. This is measured on a scale of zero to one, where zero represents complete dependence on a single country for all fuel/energy needs (indicating a high risk of energy disruption) and one represents complete self-sufficiency (a low risk of energy disruption) for a specified fuel/energy source. The DFS is calculated as follows (Stamford and Azapagic, 2012):

$$DFS = P_{in} + P_{im}\left(1-\frac{\sum_c^C P_{im,c}(P_{im,c}-1)}{9900}\right) \quad (-) \qquad (24)$$

where:

DFS diversity of fuel supply mix (-)

P_{in} proportion of fuel consumption from domestic resources (-)

P_{im} proportion of fuel consumption from imported resources (-)

$P_{im,c}$ proportion of fuel imports supplied by exporting country c (-)

c exporting country (-)

C total number of exporting countries (-).

The DFS has been calculated for shale gas as well as the other fuels used for generating electricity in the UK. The impact of shale gas on the UK energy mix has also been assessed by calculating the DFS for the present (2012) and future (2030) UK gas and electricity mixes; for details see tables D12 and D13 in Appendix D. The DFS of the gas and electricity mix scenarios have been calculated by multiplying the DFS of each electricity option by their percentage contribution to the mix (tables D12 and D13) and then adding these together.

2.6.2. Wastewater treatment

In the UK, wastewater produced from hydraulic fracturing must be treated in a wastewater treatment plant before it can be discharged into open water bodies (DECC, 2014). As treatment works are constantly in operation, it is important that the volume of wastewater produced does not cause strain to existing facilities and overload them, as this could lead to an overflow and discharge of inadequately treated water into the environment. To assess the potential for this, the volume of wastewater produced by a shale gas well has been compared to the treatment capacity of facilities in and close to the Bowland-Hodder shale play, the main area of shale gas interest and development in the UK. A further aspect considered is the need to transport wastewater by tankers from well sites to these facilities as this would affect communities living nearby; hence the number of tanker trips required has also been calculated. The data for the estimations associated with wastewater treatment can be found in tables D15 and D16 in Appendix D.

2.6.3. Land use

Conflict over the use of land at sites of special cultural and scientific interest could have significant implications for shale gas development as such sites are protected, limiting the area available for drilling. To assess potential conflicts related to land use, a binary overlap approach has been used in which the Bowland-Hodder shale play and sites of special interest (see Table D17 in Appendix D) have been mapped out using Google Earth (2015). A map of major cities in relation to the shale play has also been plotted to identify any further land-conflict issues. The sites of cultural and scientific importance selected are:

- national parks;
- special areas of conservation (SAC);
- special protected areas (SPA);
- areas of outstanding natural beauty (AONB);
- UNESCO World Heritage sites;
- Natura2000 and Ramsar sites;
- English Heritage sites; and
- local nature reserves.

2.6.4. Regulatory staff requirements

The deep horizontal drilling and high pressure hydraulic fracturing needed for extracting shale gas are not being carried out in the UK at present. Therefore, new regulatory schemes are required to ensure compliance with standards and to avoid problems associated with well integrity, leaks, emissions and waste treatment. It has been estimated that the UK could have up to 4,000 commercial and operational shale gas wells (drilled over a period of 15 years), with 400 wells being drilled per year during peak activity (Lewis et al., 2014). Consequently, the availability of skilled staff, particularly inspectors, in regulatory bodies is critical for proper regulation enforcement (DECC, 2013). In the UK, shale gas operators must obtain a license for exploration and development from the Department of Business, Energy and Industrial Strategy (BEIS), environmental permits from relevant environment agency and numerous other permits and permissions from other regulatory bodies (DECC, 2013). Once all permits and permissions are obtained, BEIS gives the final consent on whether exploration/development can proceed (DECC, 2013; EA, 2012). As BEIS is the main regulatory body involved, the number of regulatory staff they have available has been considered here. However, other regulatory bodies such as the Environment Agency (EA) and Health and Safety Executive (HSE) would also be involved in monitoring permit and license compliance (DECC, 2013; EA, 2012).

The number of inspectors needed to ensure wells are in compliance with their permits have been estimated based on US standards, where one full time inspector should be in charge of no more than 300 wells and wells require seven inspections prior to production, a minimum of one check-up per year during production and three examinations after decommissioning (Earthworks, 2012a; Earthworks, 2012b; Western Organization of Resource Councils, 2013). If there are reports of violations or inspection failures, additional inspections will be required. Based on this, the total (minimum) number of inspections required has been calculated to determine the minimum number of inspectors needed. This estimate is compared to the number of inspectors currently employed for the regulation of the UK oil and gas industry (DECC, 2013; DECC, 2011) to assess whether current staff numbers are adequate and if and how many additional inspectors may be needed.

3. Results and discussion

3.1. Employment

3.1.1. Direct employment

The development of shale gas in the UK is expected to generate between 32,000 and 74,000 direct, indirect and induced jobs (AMEC, 2013; Taylor and Lewis, 2013). Based on the US experience (Fullenbaum et al., 2011), the majority of these are likely to be induced jobs while the number of direct jobs is expected to be relatively small, particularly in comparison with other fuel supply chains.

The estimated direct employment (DE, equation (13)) in the life cycle of shale gas electricity is compared to other sources of electricity in Table 35. As can be seen, with 48 person-years/TWh, shale gas has the lowest employment, followed by conventional gas at 62 person-years/TWh. By contrast, the highest employment of 782 person-years/TWh is provided in the life cycle of hydroelectricity. In general, the fossil fuels (bar LNG) and nuclear have a smaller DE than the renewable options. LNG has a relatively high DE because of the jobs created in the liquefaction, regasification and shipping stages. The renewables have a significantly higher DE because of the workforce needed for maintenance (wind and solar), construction (hydro) and feedstock cultivation and processing (biomass). Renewable options also tend to have a lower generation capacity than the fossil fuels and nuclear, which is why they have higher employment levels per unit electricity generated.

The DE in the different life cycle stages of shale gas electricity estimated using the data in Table D1 and equation (13), are given in Table 36. As evident, fuel extraction is the biggest source of employment, with 26.2 person-years/TWh. This is due to the numerous stages involved in the preparation of a well pad (e.g. its construction, transport and installation of equipment) and the number of wells needed to produce enough gas to sustain the power plant over its life time. The next largest contributors to DE are power plant construction and operation (13.1 and 6.8 person-years/TWh, respectively), owing to the significant workforce needed to build the power plant and its continuous operation over its lifetime. On the other hand, the number of staff needed for fuel transportation, power plant decommissioning and overhauls is low (0.2-0.8 person-years/TWh) as these activities require only a handful of engineers and site operators or are short term (up to six months).

Table 35: Direct employment in the life cycles of shale gas and other electricity options[a].

Electricity option	Direct life cycle employment, DE (person-years/TWh)
Shale gas	47.7
Conventional gas	62.0
LNG	326.88
Coal	191.0
Hydro	782.4
Nuclear	87.0
Solar PV	653.0
Offshore wind	368.0
Biomass	385.8

[a] The results for shale gas, LNG and hydroelectricity are estimated in this work. The results for the other electricity options are sourced from Stamford and Azapagic (2012).

Table 36: Number of jobs created in the life cycle of shale gas.

Life cycle stage	Number of jobs (person-years/TWh)
Fuel extraction	26.2
Fuel transportation	0.8
Power plant construction	13.1
Power plant operation	6.8
Power plant decommissioning	0.5
Overhauls	0.2

3.1.2. Local employment

Out of the above-mentioned 32,000-74,000 jobs expected to be created by shale gas exploitation, 27,500-64,000, or 86%, are estimated in this work to be available to local workforces. Local employment in the different life cycle stages ranges from 59% for drilling and hydraulic fracturing jobs to 70% for exploration and site preparation to 100% for the rest of the supply chain (Table 37). The reason for the lower local employment in some stages is because they require specialist labour which is not available locally, such as hydraulic fracturing engineers and specialised geo-scientists (Lewis et al., 2014). These specialist roles often require previous experience (Rigzone, 2014), leading to the expectation that labour for specialist jobs will more than likely need to be imported from abroad (e.g. from the US) where experienced workers can be found.

Table 37: Local employment potential in the life cycle of shale gas electricity.

Life cycle stage	Percentage local employment, P_{LE} (%)
Exploration and site preparation	70
Drilling and hydraulic fracturing	59
Extraction, treatment and preparation	100
Distribution	100
Operation of power plant	100

3.1.3. Gender equality

The gender equality (GE) index for the UK oil and gas industry, of which shale gas would be an integral part, is estimated at –0.93, reflecting the fact that the workforce is almost entirely male. In comparison, the oil and gas industry in Canada has a GE of –0.58, with a near equal split of male and female workers. Norway is the next best country for GE in this sector with –0.62, followed by the US (–0.70) and Australia (–0.76). Thus, the UK oil and gas sector is characterised by very high gender inequality. Shale gas could help to address this issue by providing new opportunities for female workers to enter the industry, but this may be limited by the availability of qualified female staff. However, if specialised workforce were to be imported from the US (see the previous section) which has a better GE than the UK, it may be possible to redress the gender balance.

3.2. Health and safety: worker injuries

As indicated in Table 38, the worker injuries in the life cycles of shale and conventional gas electricity are the lowest (WI = 0.53 and 0.54, respectively) out of all the electricity options considered, suggesting that they are the safest options from a workforce perspective. The injuries in the supply chain of LNG electricity are much higher (four times). The reason for this is that most of LNG is imported to the UK from Qatar where natural gas is extracted offshore and injury rates are higher than in the UK. In addition, the contribution of LNG transport is high (52%) because of the number of shipments needed to sustain a CCGT power plant over its lifespan.

The worst option overall is hydroelectricity, with 28 times larger WI than electricity from shale gas (Table 38). These are mainly incurred during the construction and refurbishment of the power plant and are related to the relatively high injury rates in the construction sector.

Table 38: Worker injuries in the life cycles of shale gas and other electricity options[a].

Technology	Worker injury rate, WI (injuries/TWh)
Shale gas	0.53
Conventional gas	0.54
LNG	2.10
Coal	4.50
Hydro	14.59
Nuclear	0.59
Solar PV	4.84
Offshore wind	2.30
Biomass	2.98

[a] The results for shale gas, LNG and hydroelectricity are estimated in this work. The results for the other electricity options are sourced from Stamford and Azapagic (2012).

3.3. Nuisance

3.3.1. Noise

As shown in Figure 30, the noise levels from shale gas activities in the UK are predicted to be in the range of 38–57 dB (equivalent continuous sound level) at 15 m from the site (Arup, 2014a). This is lower or comparable to common noises, such as traffic, washing machines or typical office noise, and is well below the hearing damage threshold. However, prolonged exposure would lead to adverse effect on hearing (Hays et al., 2016), although the activities which produce the most noise are temporary (hydraulic fracturing), so adverse effects to hearing are unlikely.

Figure 30 also indicates that the noise levels predicted for the UK are half the levels measured in the US (77-104 dB) at the same distance of 15 m (MDE and DNR, 2015; Vondra, 2014). This is likely because the UK noise predictions are for exploration drilling and hydraulic fracturing, while the US values are from full scale projects. Equipment and activities used in exploration/preliminary drilling and hydraulic fracturing will be smaller than that used in full scale projects and consequentially, the noise levels will be lower. However it is uncertain whether the same size and capacity equipment used in the US will be used in the UK when commercial drilling begins. Therefore, these predicted values should be treated with caution.

The distance from a well site will also have significant impacts on the level of noise experienced. The distance from residential areas is uncertain as the UK currently has no legislation on setback distances (Cave, 2015). Proposed sites, such as Roseacre Wood and Kirby Misperton, are 2 km and 635 m from residential areas (Arup, 2014b; Ross, 2015) and at these distances the noise levels (calculated using the inverse square law) would not exceed 22 and 32 dB, respectively. UK wind farms and wind turbines have no legislation for setback distances either, but a distance of 350 m is recommended, increasing up to 3 km for large turbines and farms (Cave, 2013). At these distances, shale gas noise levels would reduce to 8-37 dB and up to 19 dB, respectively. The US legislates setback distances of 150-300 m (Cave, 2015) for shale gas wells, which would correspond to noise levels of 19-44 dB and 6-35 dB. These noise levels are comparable with breathing and quiet conversations (Figure), so it is unlikely, that at these distances, noise generated by shale gas development could cause major disruptions or adverse impacts on hearing and general wellbeing (stress, anxiety, sleep). However, these estimates are based on predicted noise levels, emphasising the need for accurate predictions as they can impact on what noise reduction measures are taken.

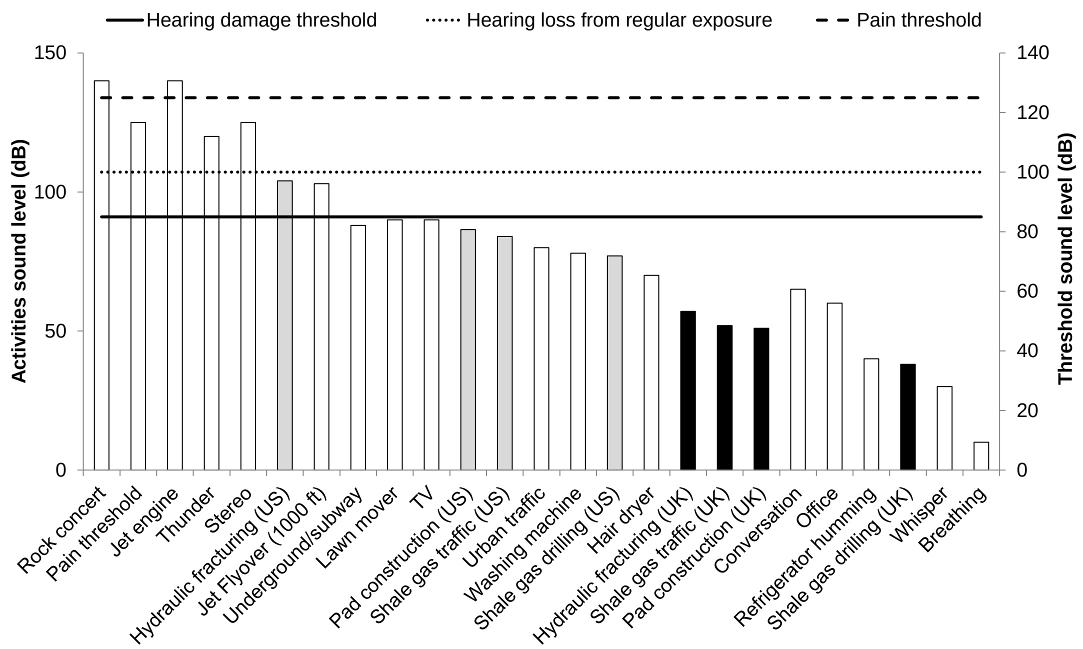


Figure 30: Predicted noise levels for shale gas activities in the UK (Arup, 2014a; MDE and DNR, 2015; Vondra, 2014)in comparison with the actual shale gas noise levels in the US (MDE and DNR, 2015; Vondra, 2014) and some other common sounds.

[UK shale-gas activities are represented by black bars and related US activities in grey bars.]

3.3.2. Traffic increase

The impact of shale gas development on traffic will depend on the road type. Based on the estimated congestion reference flow *(*CRF) for urban roads, estimated using data in tables D6 and D7, the maximum increase in traffic volume would range from 3% for urban motorways with dual carriageways (14.6 m wide) to 30% for single-lane carriageways (6.1 m). This represents the maximum impact, i.e. if all the trucks were to arrive within an hour of one another during peak hour. For rural roads, truck traffic would increase congestion by 3% and 12% for dual and single carriageways, respectively. The reason for the lower impact on rural roads and single carriageways is because they are typically busier and more congested during peak hour due to commuting.

In either case, it is important that the increase in traffic and congestion is managed to minimise the impact on local communities. To reduce strain on roads, routes should be selected specifically to avoid busy lanes and peak hours. This is also important for reducing noise, impacts on air quality and road accidents (Graham et al., 2015). Residents living close to roads identified as potential routes for transport should also be consulted to ensure that the above-mentioned impacts related to transport are minimised.

3.4. Public perception

3.4.1. Public support

As indicated in Table D8 in Appendix D, the average support for shale gas across the studies is the lowest (together with coal) and the opposition second highest (after coal). However, the number of people who are unsure about their opinion of shale gas is also high, sharing second place with LNG (after coal). These are the reasons why shale gas has the second lowest public support index (5.6%) following coal (–7%), as shown in Table 39. Solar PV, hydroelectricity and wind have the highest public support (65-72%). The high percentage of 'unsure' responses also highlights the need for increasing public knowledge and understanding of shale gas; for further discussion of this topic, see the next section.

Table 39: Estimated public support for different electricity options.

Option/energy source	**Public support index, PSI (%)**
Shale gas	5.6
Conventional gas	34
LNG[a]	15
Coal	-7
Nuclear	9
Hydro	72
Solar PV	75
Offshore wind	65
Biomass	57

[a] Survey considered support on the export of LNG in the US.

3.4.2. Media impact

With a total score of 0.65, NGOs have by far the largest estimated media impact and therefore, the largest potential to influence public opinion about shale gas. Government bodies and academic organisations considered in this work have a score of 0.35, while shale gas operators score a zero. This is not to say that operators have no presence on social media sites, but in comparison to NGOs and the other parties considered, their impact through social media appears negligible. This large difference in presence means that people are able to see more messages and information put forward by NGOs, thereby potentially skewing how the issues surrounding shale gas are framed. As over 50% of the UK population use social media (ONS, 2016; Statista, 2017b), the public's impression of shale gas is thus most likely to be shaped far more effectively by NGOs than by any other stakeholder.

3.5. Local communities

3.5.1. Spending on local suppliers

The total potential spending on local suppliers is estimated to range from 37.9-100% of the total spend (£32.12 billion) for shale development in the UK (see Table D10 in Appendix D), depending on the amount spent on hydraulic fracturing equipment, drilling rigs and directional drilling. Special equipment for hydraulic fracturing, such as high pressure pumps, high power mixers and large multi-purpose equipment, will be required and will most likely have to be imported from the US, the main producer of such specialised equipment (Calfrac, 2015; Lewis et al., 2014). As potential spending for this could total £17 billion, this significantly reduces the amount spent on local suppliers. In addition to this, the UK currently does not have enough drilling rigs for the anticipated number of wells, especially during peak drilling (House of Lords, 2014). Also, even though the UK has experience in horizontal drilling, this is in applications such as water pipelines, telecommunications and electricity cables, which are at significantly lower depths than those required for shale gas exploration.

Therefore, spending on local suppliers in the region of £12.17 billion to £15.12 billion (37.9-47.1%) is more likely; see Section DVI.I in Appendix D for more details. This will be spread throughout a 15 year period, the time required for the UK shale gas industry to reach maturity from the commencement of commercial drilling (Lewis et al., 2014). Based on this, the spending on local suppliers would average out at £0.81 billion to £1 billion per year, thereby boosting the UK's GDP by 0.04-0.05% (based on the 2015 GDP (Statista, 2017a)). This could be increased via research and development into hydraulic fracturing and directional drilling, with the aim of developing UK designed and manufactured technology. However, it should be noted that in reality spending would not be evenly distributed throughout the 15 years, but it would increase with drilling rates to a maximum (corresponding to peak drilling) and then decline.

3.5.2. Direct community investment

It has been reported that communities affected by shale gas could receive up to £2.1 billion, through the combination of the community charter and the shale gas wealth fund (HM Treasury, 2016; UKOOG, 2013). According to the community charter, local communities will receive £100,000 per well site and 1% of revenue from the sale of shale gas produced; £1.1 billion combined total (Cronin, 2013; UKOOG, 2013), both of which are considered to be a direct community investment. In the previous chapter it was estimated that local communities could receive £351,000-£665,000 per well from the community charter, which would results in £470,000-£890,000 in investment for communities per year for each well site[1].

The wealth fund is a fund paid for by shale gas tax revenue (HM Treasury, 2016), but it is uncertain what percentage of this tax revenue will go towards the fund. In addition to shale gas, communities close to power plants also benefit £4.1 million to £10 million per year from investments in sponsored events and other community activities (npower, 2017). Thus, over the whole life cycle of shale gas electricity, the total direct community investment is estimated in the range of £4.6 million to £10.9 million per year, representing 0.73–2.23% of the total annual revenue generated by shale gas and power plant operators. This is arguably a small percentage of their revenue and more could be given back to local communities. Who exactly will receive the money is uncertain as the community charter and wealth fund do not specify whether individual households or local councils or both will be the beneficiaries.

However, even a moderate contribution to communities is likely to be beneficial at a time when many local councils are facing budget cuts from central Government. For example, Lancashire County Council – one of the main UK councils facing shale gas development activity – had a net 2015/16 budget of £726.7 million and must save £152 million by 2018 (Lancashire County Council, 2015). Similarly, Salford City Council – another area where exploration of shale gas is proposed – had a budget for 2015/16 of £207.7 million and has been forced to reduce expenditure by over £149 million since 2010/11 (Salford City Council, 2015).

3.6. Infrastructure and resources

3.6.1. Diversity of fuel supply

Shale gas is a completely indigenous fuel for the UK, thereby scoring a maximum score of one for the diversity of fuel supply, DSF (Table 40). Therefore, if it were to displace gas imports in the UK gas mix, energy security would increase. For that reason, the DSF is higher for the scenario assuming high rather than low shale gas penetration in the gas mix (0.92 vs 0.82); see Table 41. However, it should be noted that the DFS decreases for both in comparison to the 2012 gas mix (0.94). The reason for this is twofold. Firstly, domestic gas production decreases in 2030, from 46.6 billion cubic metres (bcm) in 2012 to 45.8 bcm in the high shale scenario and 22.7 bcm in the low shale scenario. Secondly, there is

[1] A well site consists of ten well pads, with each pad containing four horizontal wells; 40 wells in total. The lifespan of a well is 30 years.

a reduction in the number of countries exporting gas to the UK (three in 2030 as opposed to four in 2012).

When the impact on electricity is considered, the mix with more shale gas has a higher DFS (0.93 vs 0.90), following the trend from the gas mix. However, unlike the gas mix, the DFS of the 2030 electricity mix improves upon that of the 2012 mix (0.90); see Table 41. However, this is primarily due to the decline in coal generation and the increase in renewable capacity, which score the maximum score for DFS (Table 40).

Therefore, these results suggest that the DSF and related security of gas supply are likely to remain unaffected or deteriorate in the future, depending on the amount of shale gas produced. On the other hand, the energy security of the future electricity mix is likely to improve regardless of shale gas. Consequently, shale gas does not present a notable opportunity for increased energy security, unless the volume produced increases significantly above current predictions.

Table 40: Diversity of fuel supply (DFS) scores for the different fuel sources used to generate electricity in the UK for the present (2012) situation and future (2030) scenarios.

Fuel	**DFS (-)**	
	2012	*2030*
Shale gas	1.00	1.00
Conventional gas (UK North Sea)	1.00	1.00
Conventional gas pipeline imports	0.38	0.36
Conventional gas liquefied natural gas imports	0.04	0.04
Coal[a]	0.86	0.86
Nuclear[a]	0.85	0.85
Hydro	1.00	1.00
Offshore wind	1.00	1.00
Solar PV	1.00	1.00
Biomass[a]	0.96	0.96

[a] The 2030 *DFS* was assumed to be the same as in 2012 due to a lack of data on future supply mix.

Table 41: Diversity of fuel supply (DFS) scores of the different gas and electricity mix scenarios considered in this work.

Scenario	**DFS (-)**
2012 gas mix	0.94
2030 gas mix (high shale gas)	0.92
2030 gas mix (low shale gas)	0.82
2012 electricity mix	0.90
2030 electricity mix (high shale gas)	0.93
2030 electricity mix (low shale gas)	0.90

3.6.2. Wastewater treatment

Previous studies on shale gas wastewater have focused on determining its complex composition (high salinity, total dissolved solids and chemicals) and the issues this causes for treatment facilities (Akob et al., 2016; Parker et al., 2014). However, no studies have attempted to quantify the strain it could have on the ability of treatment facilities to fully treat wastewater produced during shale gas extraction.

The amount of wastewater produced over a well's lifespan ranges widely, from 871-75,000 m^3 (see Table D15 in Appendix D). In order to transport this from the well site to the treatment facility, tankers (21-43.9 m^3) will be needed (Study Hills, 2012). This will require 19-3,606 truck trips, contributing to an increase in traffic near the treatment plants and the well site. However, as mentioned earlier, wastewater shipments are not included in the estimation of traffic congestion due to the uncertainties in the volume of water generated. On-site treatment of wastewater could further mitigate the impact of wastewater transport on congestion, but would also increase the capital and operating cost of the well.

In terms of strain on treatment facilities, depending on the capacity of the nearest suitable treatment plant, this work estimates that it would take between 0.02-97.35 hours to treat the total volume of wastewater produced by a well (Table D16 in Appendix D). This would increase the pressure on facilities, especially as they are in continuous operation 24 hours a day. It will also affect storage capacity at facilities, as the wastewater cannot be treated in one go (due to complex composition) without overloading the facilities during normal operation. One way of managing wastewater treatment is to spread out deliveries over the well's lifespan of 30 years. The rate at which wastewater returns to the surface is not constant, with the majority of injected fluid resurfacing within the first month of well completion. Up to 40% (10,000 m^3) of the injected fluid resurfaces, which would require 481 tankers to transport, representing the maximum in wastewater production and tanker trips. When spread out over a month, a maximum of 18 tanker trips to transport 357 m^3 of wastewater each day would be needed. This corresponds to 0.1-4.0% of the capacity of the treatment facilities (Table D16 in Appendix D). However, this is the impact of one well; it is predicted that 4,000 wells could be drilled in the UK over a period of 15 years (Lewis et al., 2014), which could put enormous strain on treatment facilities. Also, the wastewater has a complex composition which is beyond the capability of most facilities. Therefore, shale gas wastewater will likely increase the potential of wastewater not being properly treated and hazardous chemicals being discharged into water bodies.

3.6.3. Land use

As shown in Figure 31, the Bowland-Hodder shale play overlaps many areas of special value and interest. These include the Peak District and North York Moors National Parks and areas of outstanding natural beauty (Forest of Bowland, Nidderdale and Howardian Hills). Sites of cultural importance also overlap, or are nearby, the shale play, including World Heritage sites (Saltaire and Liverpool – Maritime Mercantile City) and English Heritage sites (Goodshaw Chapel, Sandbach Crosses, Roche Abbey). However, it is local nature reserves that will be the most affected, as can be seen in Figure 31. Consequently, it is likely that shale gas operators could experience stronger opposition and resilience from anti-shale activists and conservationists due to the importance of such sites.

The shale play also overlaps major cities and towns as shown in Figure 32. Cities such as Liverpool, Manchester and York lie within the shale play while others, such as Leeds and Leicester, are located close by. This will also reduce the area available for drilling as there could be strong opposition to development close to urban areas.

Therefore, the area available and suitable for shale gas development will likely be limited to a small number of sites, which could amplify impacts such as noise, traffic and pollution. Similar conclusions were drawn by Clancy et al. (2017) who found that, depending on setback distances, a large proportion (74%) of land will be unsuitable for drilling.

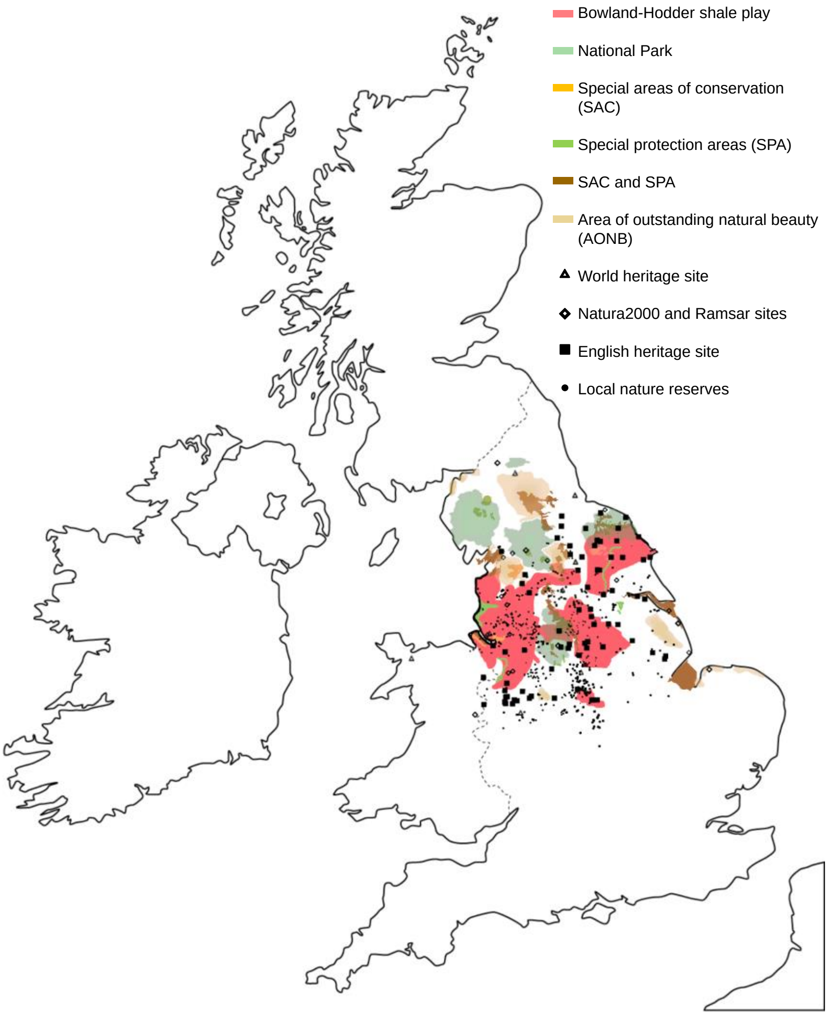


Figure 31: Map of Bowland-Hodder shale play and areas/sites of special value and importance (Andrews, 2013; National Parks, 2013; Natural England, 2013; Google Earth, 2015).

Figure 32: Major cities and towns in the vicinity of the Bowland-Hodder shale play (Andrews, 2013; Google Earth, 2015).

[The shale play shown in red.]

3.6.4. Regulatory staff requirements

A well with a production lifespan of 30 years would require a minimum of 40 inspections over its lifespan. Based on this and the 4,000 wells expected to be drilled (Lewis et al., 2014), the UK shale gas industry would require a minimum of 160,000 inspections. Therefore, it is important that the regulatory system in place is adequately staffed to be able to cope with the large number of inspections required. As one full time inspector should be in charge of no more than 300 wells, this would result in a minimum requirement of 14 full time inspectors needed for the UK shale gas industry (Western Organization of Resource Councils, 2013). Additional support staff will also be needed, such as administrative personnel.

Whilst this number of inspectors seems low, the US experience has shown that the large well-to-inspector ratio overwhelms the capability of regulatory staff, with inspection-to-inspector ratios in the range 270-2,450. This has resulted in many wells failing to meet the minimum requirement of one inspection per year, in turn leading to violations slipping through without detection (Earthworks, 2012a; Earthworks, 2012b). At the time of writing, BEIS, the relevant regulatory body, has a total of 63 environmental regulatory staff (technical and non-technical), including seven inspectors, and carries out 60-150 inspections per year on the UK continental shelf. This equates to 9-21 inspections per inspector (DECC, 2011). The Environment Agency and Health and Safety Executive would also be involved in regulating different stages of shale gas extraction. If or when the shale gas industry takes off in the UK, the inspection ratio will increase significantly and, therefore, it is imperative that staffing numbers increase to keep up with demand. However, it should be noted that training of regulators is a key issue associated with regulation. In the US, a training initiative was launched to train regulators and policy makers, but this initiative is being partially funded by ExxonMobil and General Electric (Olson et al., 2012). This may cause concern for the general public as it could be seen as a form of self-regulation and undermine the trust in regulation. Therefore it is important for regulatory staff training and education to be funded and run by neutral bodies, such as Government agencies.

4. Conclusions

This study has considered the social sustainability of developing shale gas in the UK and using it to generate electricity. In total, 14 indicators have been used to analyse impacts on employment, health and safety, nuisance, public perception, community impacts and infrastructure and resources.

The results suggest that the main benefits that could arise from shale gas production and utilisation stem mostly from job creation and financial gains for communities impacted by development. Overall, a significant number of jobs could be created; however, the majority of these are temporary, contributing little to direct employment. Despite this, the long-term jobs created are well paid, particularly in the gas production and distribution stages (is in line with the rest of the oil and gas sector) as well as in the electricity generation stage. Also, a large proportion of the jobs created could be sourced from local workforces. Therefore, to maximise the benefits created through employment, it is important to source labour locally or domestically. Another way of maximising employment gains is to train personnel for roles which require specialised labour.

The other main benefit of shale gas development is related to financial gains to communities. Communities stand to benefit from direct investment through funds and charters, as well as increased trade for local businesses. This would primarily provide boosts to local economies in areas affected by shale gas development. However, it is important that the distribution of the investment into communities is equitable and transparent, to ensure their use to the best effect for all affected by the development, while minimising the potential for the mismanagement of funds.

Additional benefits of shale gas are related to health and safety. In comparison to other electricity options, it is the safest industry from a workforce perspective, as it has the lowest worker injury rate. This is because the jobs across the life cycle of shale gas are in sectors which have lower accident rates than those involved in the stages of other electricity options, such as construction and mining. Furthermore, as shale gas is a completely indigenous fuel source, it could help increase (or maintain) energy security in the UK. However, this will depend on the volume produced and on what the future energy mix is made up of; increase in renewables and drop in coal would also improve energy security of UK electricity.

One of the disadvantages of shale gas is a high potential for inadequate treatment in wastewater facilities, which could release substances harmful to humans and the environment into water bodies. This is due to the large volume of wastewater produced by a well and the large number of wells expected to be drilled, coupled with the complex composition of wastewater, with high salinity and a cocktail of chemicals. The development of shale gas could also overwhelm regulatory bodies, as at least 160,000 well inspections would be required over a period of over 30 years.

Furthermore, there could be land conflict over development because the main shale play spans many sites of special value and interest. This could result in the concentration of development in specific areas, which could lead to an amplification of the impacts from noise, traffic and wastewater. The use of heavy machinery and the need to bring in and out equipment and materials by trucks will cause disruption to those who live close to well sites and along roads being used for transport. The activities which generate the most noise and traffic are temporary, but if development is concentrated, it could lead to prolonged periods of drilling, hydraulic fracturing and heavy traffic. This would do little to improve the UK public's opinion of shale gas, which is currently not favourable.

Therefore, if shale gas was to be developed in the UK, it is imperative that appropriate mitigation measures are in place to reduce the societal (and other) impacts while also developing strategies to maximise the benefits that could be created. Mitigation measures include: minimising noise through housing diesel powered generators in acoustic sheds and using acoustic fencing around the well sites; using roads during non-peak hours; onsite wastewater treatment via membrane filtration or reverse osmosis prior to delivery to treatment plant; better balance of information presented about shale gas and more effective communication by those involved in developing shale gas; communication strategies which build trust between developers and communities affected and the general public. Measures to maximise the benefits include: specialised skills and training centres for shale gas extraction; research and development into hydraulic fracturing and directional drilling technology; consultation with communities on how charters/funds should be distributed and spent equitably.

Overall, this work finds that while there are opportunities for the UK to benefit from developing shale gas, there are many social issues which need to be addressed. In the event of shale gas development processing into commercial exploration, it is up to the Government and industry to address the social issues identified in this work, as well as develop strategies to maximise the benefits.

Nomenclature

AADT	the annual average daily traffic flow (vehicles/day)
AAWT	the annual average weekday flow (vehicles/day)
CRF	congestion reference flow (vehicles/day)
CAP	maximum vehicle capacity per road lane (vehicles/day)
c	exporting country (-)
C	total number of exporting countries (-).
DFS	diversity of fuel supply mix (-)
DE	total direct employment generated in the life cycle of shale gas electricity along the supply chain (person-years/kWh)
DE_i	number of jobs created in life cycle stage *i* (no. of persons)
E_i	employment in life cycle stage *i* (person-years/TWh)
FW	percentage of female workforce (%)
GE	gender equality index (-)
i	life cycle stage (-)
I	total number of life cycle stages (-).
j	metric type (e.g. tweets, 'likes', etc.)
J	total number of the types of social media metrics (-)
L	number of lanes on the road (-)
LE	number of employees that could be hired from the local community (persons-years/TWh)
LI	annual investment in and donations to the local community (£/year)
MI_s	total media impact of stakeholder *s* (-)
m	social media platform (-)
M	total number of social media platforms (-)
$n_{s,j}$	amount in metric type *j* (e.g. number of tweets, 'likes', etc.) by stakeholder *s* (-)
$n_{j\,(max)}$	the highest amount in metric type *j* (-)
P_{tot}	total amount of electricity generated over the lifetime of the power plant (TWh)
P_{LE}	proportion of employees that could be hired from the local community (%)
PkF	proportion of daily traffic flow during peak hours (-)
PkD	the directional split of flow during peak hours (-)
P_S	total presence of stakeholder *s* on all social media considered (-)
P_T	total presence of all stakeholders on all social media considered (-)
$P_{s,j}$	presence of stakeholder *s* for type of metric *j* (-)
P_{LS}	percentage of total spending on local suppliers (%)
P_{LI}	percentage of direct investment into the local community (%)
P_{in}	proportion of fuel consumption from domestic resources (-)
P_{im}	proportion of fuel consumption from imported resources (-)

$P_{im,c}$ proportion of fuel imports supplied by exporting country c (-)

r_i annual injury rate in life cycle stage *i* (injuries/person-years)

R_T total annual revenue (£/year)

s stakeholder (-)

S_{LS} total spending on local suppliers (£)

S_T total expenditure (£).

t_i duration of employment in life cycle stage *i* (years)

TE total number of employees needed (persons-years/TWh)

WI number of worker injuries (injuries/TWh)

W_f width factor – width of road lanes relative to a standard width of 3.65 m (-)

References

Adamus, W. and Florkowski, W. J. **2016**. The evolution of shale gas development and energy security in Poland: Presenting a hierarchical choice of priorities. *Energy Research and Social Science*, 20, 168-178.

Akob, D. M., Mumford, A. C., Orem, W., Engle, M. A., Klinges, J. G., Kent, D. B. and Cozzarelli, I. M. **2016**. Wastewater disposal from unconventional oil and gas development degrades stream quality at a West Virginia injection facility. *Environmental Science and Technology*, 50, 5517-5525.

AMEC. **2013**. *Strategic Environmental Assessment for Further Onshore Oil and Gas Licensing*. *Department of Energy and Climate Change*. London. Retrieved from.

Andrews, I. J. **2013**. *The Carboniferous Bowland Shale gas study: geology and resource estimation*. *British Geological Society*. London, UK. Retrieved from.

Arredondo-Ramírez, K., Ponce-Ortega, J. M. and El-Halwagi, M. M. **2016**. Optimal planning and infrastructure development for shale gas production. *Energy Conversion and Management*, 119, 91-100.

Arup. **2014a**. *Environmental statement: Appendix P- Noise*. *Cuadrilla Elswick Ltd*. Manchester, UK. Retrieved from: http://www.cuadrillaresources.com/our-sites/locations/roseacre-wood/.

Arup. **2014b**. *Temporary Shale Gas Exploration at Roseacre Wood, Lancashire- Environmental Statement- Volume 1*. *Cuadrilla Elswick Ltd*. Preston, UK. Retrieved from: http://www.cuadrillaresources.com/our-sites/locations/roseacre-wood/.

Barber, J. R., Burdett, C. L., Reed, S. E., Warner, K. A., Formichella, C., Crooks, K. R., Theobald, D. M. and Fristrup, K. M. **2011**. Anthropogenic noise exposure in protected natural areas: estimating the scale of ecological consequences. *Landscape Ecology*, 26, 1281-1295.

Barber, J. R., Crooks, K. R. and Fristrup, K. M. **2010**. The costs of chronic noise exposure for terrestrial organisms. *Trends in Ecology and Evolution*, 25, 180-189.

Behrer, A. P. and Mauter, M. S. **2017**. Allocating Damage Compensation in a Federalist System: Lessons from Spatially Resolved Air Emissions in the Marcellus. *Environmental Science and Technology*, 51, 3600-3608.

Broderick, J., Anderson, K., Wood, R., Gilbert, P. and Sharmina., M. **2011**. *Shale gas: an updated assessment of environmental and climate change impacts*. *Tyndall Centre for Climate Change and Research*. Manchester. Retrieved from.

Calfrac. **2015**. *Fracturing equipment profiles* [Online] Denver, CO, USA. Available: http://www.calfrac.com/Customer-Centre/Service-Line-Equipment/Fracturing-Equipment-Profiles/index.php [Accessed April 2017].

Castell, S., Charlton, A., Clemence, M., Pettigrew, N., Pope, S., Quigley, A., Shah, J. N. and Silman, T. **2014**. *Public Attitudes to Science 2014*. *Ipsos MORI*. London. Retrieved from.

Cave, S. **2013**. *Wind turbines: Planning and separation distances*. *Northern Ireland Assembly* Belfast, NIR. Retrieved from: http://www.niassembly.gov.uk/globalassets/documents/raise/publications/2013/environment/12813.pdf.

Cave, S. **2015**. *Proximity of petroleum exploration wells to dwellings*. *Northern Ireland Assembly*. Belfast, NIR. Retrieved from: http://www.niassembly.gov.uk/globalassets/documents/enterprise-trade-and-investment/hydraulic-fracturing/20150304-assembly-research---petroleum-wells.pdf.

Clancy, S. A., Worrall, F., Davies, R. J. and Gluyas, J. G. **2017**. An assessment of the footprint and carrying capacity of oil and gas well sites: The implications for limiting hydrocarbon reserves. *Science of The Total Environment*, In Press- Corrected Proof.

Cronin, K. **2013**. *Community engagement charter oil and gas from unconventional reservoirs*. *UK Onshore Oil and Gas (UKOOG)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/256360/Publication_UKOOG_communityengagementcharterversion6.pdf.

DECC. **2011**. *Offshore oil and gas in the UK: an independent review of the regulatory regime Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/publications/offshore-oil-and-gas-in-the-uk-independent-review-of-the-regulatory-regime.

DECC. **2013**. *Onshore oil and gas exploration in the UK: regulation and best practice*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/503067/Onshore_UK_oil_and_gas_exploration_England_Dec15.pdf.

DECC. **2014**. *Fracking UK shale: water*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/277211/Water.pdf.

EA. **2012**. *Guidance note: Regulation of exploratory shale gas operations*. *Environment Agency (EA)*. Bristol, UK. Retrieved from: http://www.groundwateruk.org/downloads/EA_ShaleGasRegulation.pdf.

Earthworks. **2012a**. *Pennsylvania Department of Environmental Protection Enforcement Report: Inadequate enforcement guarantees irresponsible oil and gas development in Pennsylvania*. *Pennsylvania Department of Environmental Protection*. Washington DC. Retrieved from: https://www.earthworksaction.org/files/publications/FINAL-PA-enforcement-sm.pdf.

Earthworks. **2012b**. *Pennsylvania oil and Gas Enforcement- Inspections* [Online] Washington DC: Pennsylvania Department of Environmental Protection. Available: https://www.earthworksaction.org/issues/detail/pennsylvania_oil_gas_enforcement_inspections#.Vl8Md7_U2iw [Accessed April 2017].

Fullenbaum, R. F., Larson, J. W. and Dorsey, J. **2011**. *The Economic and Employment Contributions of Shale Gas in the United States*. *IHS Global Insight (USA)*. Washington DC. Retrieved from.

Gao, J. and You, F. Design and optimization of shale gas energy systems: Overview, research challenges, and future directions. *Computers & Chemical Engineering*.

Goodman, P. S., Galatioto, F., Thorpe, N., Namdeo, A. K., Davies, R. J. and Bird, R. N. **2016**. Investigating the traffic-related environmental impacts of hydraulic-fracturing (fracking) operations. *Environment International*, 89-90, 248-260.

Google Earth. **2015.** UK *Google Earth 7.1.5.1557 Google Earth 7.1.5.1557* Google Inc:

Graham, J., Irving, J., Tang, X., Sellers, S., Crisp, J., Horwitz, D., Muehlenbachs, L., Krupnick, A. and Carey, D. **2015**. Increased traffic accident rates associated with shale gas drilling in Pennsylvania. *Accident Analysis and Prevention*, 74, 203 - 209.

Hays, J., McCawley, M. and Shonkoff, S. B. C. **2016**. Public health implications of environmental noise associated with unconventional oil and gas development. *Science of The Total Environment*, 580, 448-456.

HM Treasury. **2016**. *Shale wealth fund: consultation*, London, UK.

House of Lords. **2014**. *The economic impact on UK energy policy of shale gas and oil*. May, 2014. *House of Lords: Economic Affairs Committee*. London, UK. Retrieved from: http://www.publications.parliament.uk/pa/ld201314/ldselect/ldeconaf/172/172.pdf.

Johnson, C. and Boersma, T. **2013**. Energy (in)security in Poland the case of shale gas. *Energy Policy*, 53, 389 - 399.

Jones, I. L., Bull, J. W., Milner-Gulland, E. J., Esipov, A. V. and Suttle, K. B. **2014**. Quantifying habitat impacts of natural gas infrastructure to facilitate biodiversity offsetting. *Ecology and Evolution*, 4, 79-90.

Lancashire County Council. **2015**. *2015-16 Revenue budget - Precepts and council tax - and cash limits covering report*. *Lancashire County Council,*. Lancaster, UK. Retrieved from: http://council.lancashire.gov.uk/mgAi.aspx?ID=27315#mgDocuments.

Lewis, C., Speirs, J. and MacSweeney, R. **2014**. *Getting ready for UK shale gas: Supply chain and skills requirements and opportunities*. *United Kingdon Onshore Oil and Gas and Ernst and Young*. London. Retrieved from.

MDE and DNR. **2015**. *Assessment of risks from unconventional gas well development in the Marcellus Shale of Western Maryland- Appendix F Noise and visual risks*.

Maryland Department of the Environment (MDE) and Maryland Department of Natural Resources (DNR). Baltimore, MD, USA. Retrieved from: http://www.mde.state.md.us/programs/Land/mining/marcellus/Pages/Risk_Assessment.aspx.

National Parks. **2013**. *Maps* [Online] Cardiff, UK: National Parks UK. Available: http://www.nationalparks.gov.uk/visiting/maps [Accessed April 2017].

Natural England. **2013**. *Improvement programme for England's Natura 2000 Sites: Natura 2000 map (IPENSINFO2)* [Online] Worcester, UK: Natural England. Available: http://publications.naturalengland.org.uk/publication/5412847253192704 [Accessed April 2017].

NIDCD. **2010**. *Common Sounds*. (Bethesda, MD, USA). Available from: http://www.nidcd.nih.gov/health/education/teachers/pages/common_sounds.aspx (Last accessed on.

npower. **2017**. *RWE in the UK: CR Report*. *npower*. Swindon, UK. Retrieved from: https://www.npower.com/home/about-npower/our-responsibility/.

O'Hara, S., Humphrey, M., Andersson-Hudson, J. and Knight, W. **2015**. *Public perception of shale gas extraction in the UK: Two years on from the Balcombe protests*. *University of Nottingham*. Nottingham, UK. Retrieved from: http://bettersociety.net/images/Public%20Perceptions%20of%20shale%20gas%20in%20the%20UK%20sept131015MH.WK.JA-H.pdf.

Oil and Gas UK. **2015**. *UK continental shelf offshore workforce demographics report 2015*. *Oil and Gas UK*. London, UK. Retrieved from: http://oilandgasuk.co.uk/wp-content/uploads/2015/08/EM014.pdf.

Olson, H. C., Tutuncu, A. N. and Ladlee, J. **2012**. *Pooling training for shale gas development (Conference)*. World Gas Conference 2012. June 2012 Kuala Lumpur. Petroleum Economist 34-35.

ONS. **2016**. *Overview of the UK population: February 2016*. *Office for National Statistics (ONS)*. London, UK. Retrieved from: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/articles/overviewoftheukpopulation/february2016.

Parker, K. M., Zeng, T., Harkness, J., Vengosh, A. and Mitch, W. A. **2014**. Enhanced formation of disinfection by-products in shale gas wastewater-Impacted drinking water supplies. *Environmental Science and Technology*, 48, 11161-11169.

Rigzone. **2014**. *Search for job opportunities* [Online] Houston, TX, USA. Available: http://www.rigzone.com/jobs/search_jobs.asp [Accessed April 2017].

Ross, A. **2015**. I won't try to block fracking plans, says North Yorkshire MP. *The York Press*, 7 October 2015, Available from: http://www.yorkpress.co.uk/news/13807202.I_won_t_try_to_block_fracking_plans__says_North_Yorkshire_MP/.

Salford City Council. **2015**. *Budget report 2015 to 2015*. *Salford City Council*. Salford, UK. Retrieved from: https://www.salford.gov.uk/budget-2015-2016.htm.

Small Business Trends. **2015**. *Interesting statistics for the top 10 social media sites* [Online] Medina, OH, USA. Available: http://webtrends.about.com/od/socialnetworkingreviews/tp/Social-Networking-Sites.htm [Accessed April 2017].

Social Media Today. **2015**. *The world's 21 most important social media sites and apps in 2015* [Online] Washington DC. Available: http://www.socialmediatoday.com/social-networks/2015-04-13/worlds-21-most-important-social-media-sites-and-apps-2015 [Accessed April 2017].

Stamford, L. and Azapagic, A. **2012**. Life cycle sustainability assessment of electricity options for the UK. *International Journal of Energy Research*, 36, 1263-1290.

Standards for Highways. **1997**. *Traffic flow ranges for use in the assessment of new rural roads*.

Standards for Highways. **1999**. *Traffic capacity of urban roads*.

Statista. **2017a**. *Gross domestic product at current market prices of the United Kingdom (UK) from 2000 to 2015 (in million GBP)* [Online] New York, NY, USA. Available: https://www.statista.com/statistics/281744/gdp-of-the-united-kingdom-uk-since-2000/ [Accessed January 2017].

Statista. **2017b**. *Number of social network users in the United Kingdom from 2014 to 2018 (in millions)* [Online] London, UK. Available: https://www.statista.com/statistics/278413/number-of-social-network-users-in-the-united-kingdom/ [Accessed April 2017].

Study Hills. **2012**. *What is tank truck?* [Online]. Available: http://www.studyhills.com/topic/1223/what-is-tank-truck [Accessed April 2017].

Taylor, C. and Lewis, D. **2013**. *Getting shale gas working*. *Institute of Directors*. London. Retrieved from.

ter Mors, E., Terwel, B. W. and Daamen, D. D. L. **2012**. The potential of host community compensation in facility siting. *International Journal of Greenhouse Gas Control*, 11, Supplement, S130 - S138.

UKOOG, **2013**, *United Kingdom Onshore Oil and Gas launches shale community engagement charter* [Press release] London, UK: United Kingdom Onshore Oil and Gas (UKOOG). Available: http://www.ukoog.org.uk/about-ukoog/press-releases/58-united-kingdom-onshore-oil-and-gas-launches-shale-community-engagement-charter.

Vondra, C. F. **2014**. *Hydraulic fracturing and North American shale plays- some concerns (Conference)*. 87th Annual soil management and land valuation May 21 2014 Ames, IA, USA. Iowa State University.

Western Organization of Resource Councils. **2013**. *Law and Order in the oil and gas field: A review of the inspection and enforcement programs on five Western States 2013 update*. *Western Organization of Resource Councils*. Billings, MO, USA. Retrieved from: http://worc.org/userfiles/file/Oil%20Gas%20Coalbed%20Methane/Law&Order2013.pdf.

Wetherell, D. and Evensen, D. **2016**. The insurance industry and unconventional gas development: Gaps and recommendations. *Energy Policy*, 94, 331-335.

Chapter 6. The overall sustainability of UK shale gas and other electricity options - current situation and future scenarios

This paper has been submitted to the journal *Science of the Total Environment* for publication and is currently under review.

This paper presents the assessment of the overall sustainability of shale gas electricity, based on three aspects: environmental, economic and social. Shale gas is assessed on these three aspects based on the results from the previous three chapters and is compared with other electricity options to determine how sustainable it is. The impact on the overall sustainability of the electricity grid mix is also taken into consideration. The introduction, tables and figures have been amended to fit into the structure of this thesis. The thesis author is the main author of the paper and is the multi-criteria decision analysis practitioner who built the models. The thesis author wrote the original manuscript. The co-authors are the supervisors of this PhD project and contributed towards the paper by reviewing the original manuscript and giving guidance on what scenarios to consider when assessing the sustainability of shale gas.

The overall sustainability of UK shale gas and other electricity options - current situation and future scenarios

Jasmin Cooper, Laurence Stamford, Adisa Azapagic*

School of Chemical Engineering and Analytical Science, The University of Manchester, The Mill, Room C16, Sackville Street, Manchester, M13 9PL (UK)

*E-mail: adisa.azapagic@manchester.ac.uk

Abstract

Many countries are considering the exploitation of shale gas but its overall sustainability is currently unclear. This study integrates environmental, economic and social aspects of shale gas to evaluate its overall sustainability. Shale gas is compared to other electricity options and for the current situation and future scenarios up to the year 2030, to investigate whether it can contribute towards a more sustainable electricity mix in the UK. The results obtained through multi-criteria decision analysis suggest that when equal importance is assumed for each of the three sustainability aspects, shale gas ranks seventh out of the nine electricity options, with wind and solar PV being the best and coal the worst options. Changing the importance of the sustainability aspects, the ranking of shale gas ranges between fourth and eighth. In order for it to become the most sustainable option of those assessed, large improvements would be needed including a 329-fold reduction in environmental impacts and 16 times higher employment, along with simultaneous large changes (up to 10,000 times) in the importance assigned to each criterion. Similar changes would be needed if it were to be comparable to conventional gas, liquefied natural gas, biomass, nuclear power or hydroelectricity. The results also suggest that a future electricity mix (2030) would be more sustainable with a lower rather than a higher share of shale gas.

Keywords: shale gas; fracking; hydraulic fracturing; electricity; sustainability; multi-criteria decision analysis

1. Introduction

This work builds on the work presented in the previous three chapters by integrating the results, to assess the overall sustainability of UK shale gas using multi-criteria decision analysis (MCDA). In total, 18 sustainability indicators are considered, of which 11 are environmental, three economic and four social. Based on these indicators, shale gas and the other electricity options considered in the previous chapters are evaluated on how sustainable they are. The impact of shale gas to grid electricity is also considered. The methods used in the study are outlined in the next section. The results and discussion are presented in Section 3 and conclusions in Section 4.

2. Methodology

2.1. Multi-criteria decision analysis

The simple multi-attribute rating technique (SMART) method has been chosen for the assessment because it is relatively simple to implement and can accommodate a large number of criteria and alternatives being considered. It involves the following steps (Edwards, 1977):

1. identification of the goal(s) to be met;
2. identification of the options to be compared;
3. identification of the decision criteria;
4. scoring of the criteria in the order of importance (increasing from a score of 10 for the lowest importance onwards) and estimation of their weights of importance;
5. rating of the options on a scale of 0 (worst) to 1 (best);
6. estimation of the overall scores and ranking of the options on a scale from 0 (worst) to 1 (best); and
7. identification of the best option.

The two main goals of this study are:

i) to assess the overall sustainability of shale gas relative to the other electricity options in the UK: conventional gas, liquefied natural gas (LNG), coal, nuclear, hydroelectricity, solar PV, wind and biomass; and

ii) to investigate how its deployment could affect the sustainability of a future UK electricity mix, taking into account potential levels of shale gas penetration.

The MCDA has been carried out using the Web-HIPRE tool (Mustajoki and Hamalainen, 2000) based on the decision tree shown in Figure 33. The sustainability aspects and indicators have been weighted based on their assumed relative importance and the options rated based on their performance in each indicator (see Table 42) using value factions. Two types of value functions have been applied to investigate the effect on the overall ranking of the options: linear and exponential. The calculated weightings and ratings have then been used to estimate the overall sustainability score – the option with the highest score is considered the most sustainable and vice versa. For further details on the SMART methodology, see Appendix EI.

In the base case, it is assumed that all three sustainability aspects (environmental, economic and social) are equally important, assigning each a weighting of 0.33; the effects of changing the importance of the aspects have been assessed in a sensitivity analysis. A further analysis has also been carried out to find out how much the weightings would need to change for shale gas to emerge as the most sustainable option overall, or to be comparable with conventional gas, renewables or nuclear power. The required improvements in the performance of shale gas for some key indicators (e.g., reductions in environmental impacts and costs and improvements in job creation) have also been considered.

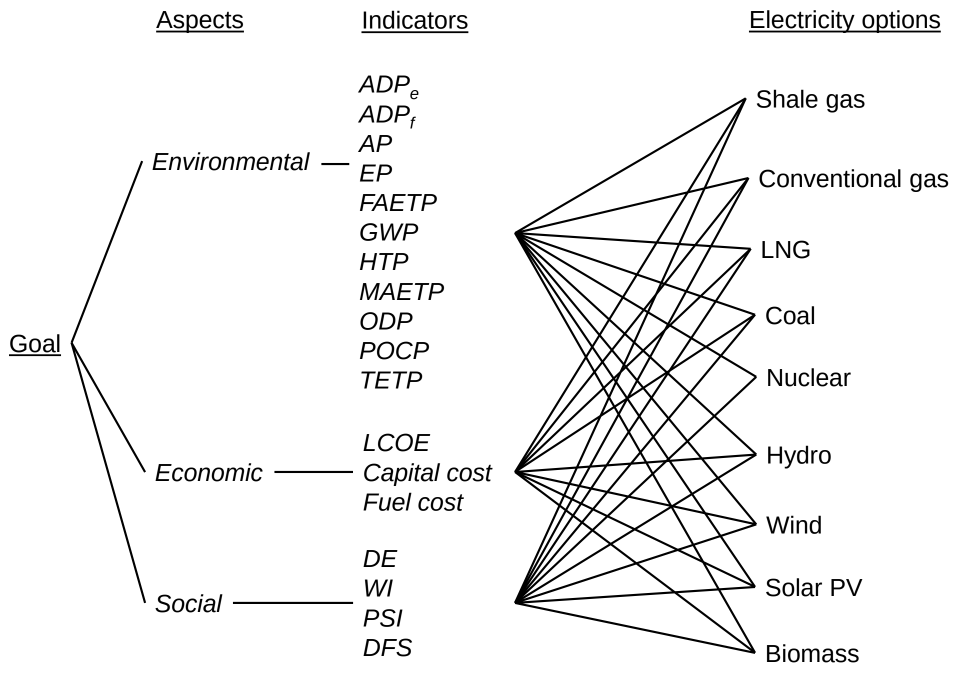


Figure 33: MCDA decision tree, showing the sustainability aspects, indicators and electricity options considered in the analysis.

[Goals: i) to assess the overall sustainability of shale gas relative to the other electricity options in the UK; ii) to find out how its deployment could affect the sustainability of a future UK electricity mix. Indicators: ADP_e: abiotic depletion of elements; ADP_f: abiotic depletion of fossil fuels; AP: acidification potential; EP: eutrophication potential; FAETP: freshwater aquatic ecotoxicity; GWP: global warming potential; HTP: human toxicity potential; MAETP: marine aquatic ecotoxicity potential; ODP: ozone depletion potential; POCP: photochemical oxidant creation potential; TETP: terrestrial ecotoxicity potential; LCOE: levelised costs of electricity; DE: direct employment; WI: Worker injuries; PSI: public support index; DFS: diversity of fuel supply.]

2.2. Data and assumptions

Two MCDA models have been constructed in Web-HIPRE, one comparing shale gas with the other electricity options (Figure 33) and another comparing the present and future electricity mixes. The former is based on the data summarised in Table 42; for definitions of the indicators, see Table E1 in Appendix E or Section 4.5 in Chapter 1. The environmental indicators have been estimated using life cycle assessment (LCA) (Chapter 3), the economic by applying life cycle costing (LCC) (Chapter 4) and the social through a social sustainability assessment (Chapter 5).

The data for the second MCDA model can be found in Table 43 and Table 44. As commercial production of shale gas is not expected in the UK until post-2020 (Lewis et al., 2014), the year 2030 has been selected for the evaluation of a future electricity mix. Two 2030 electricity scenarios are considered: one with low penetration of shale gas and another with high contribution to the mix. Data for the current and future mixes are given in Table 44.

2.3. Data quality assessment

A data quality assessment has been carried out to evaluate the overall quality of the data used in the study and, through that, the validity of the results. A pedigree matrix, typically used in LCA (Althaus et al., 2007; Weidema et al., 2013), has been applied for these purposes. The pedigree matrix rates data quality on the following six criteria on a scale from 1 (high) to 5 (low): reliability, completeness, temporal correlation, geographical correlation, technological correlation and sample size. For more detail, see Table E2 in Appendix E.

The data have been rated for each of the above criteria and averaged for each sustainability aspect (LCA, LCC and social sustainability assessment). The ratings have then been added up to calculate the overall data quality score for each sustainability aspect, ranging between six and 30 as follows:

- six to 12: high quality;
- >12 to 18: medium quality;
- >18 to 24: medium-low quality; and
- >24: low quality.

Table 42: Sustainability indicators and their estimated values for different electricity options[a].

Indicators[b]	**Shale gas**	**Conventional gas**	**Liquefied natural gas**	**Coal**	**Nuclear**	**Hydro**	**Solar PV**	**Wind**	**Biomass**
ADP_e (mg $Sb_{-Eq.}$/kWh)	0.68	0.24	0.26	0.04	0.07	0.01	10.91	0.22	0.14
ADP_f (MJ/kWh)	6.58	6.33	7.43	11.70	0.09	0.04	1.05	0.15	0.62
AP (g $SO_{2\text{-}Eq.}$/kWh)	0.35	1.71	3.41	5.13	0.06	0.01	0.43	0.06	1.39
EP (g $PO_{4\text{-}Eq.}$/kWh)	0.17	0.06	0.06	1.86	0.02	0.01	0.29	0.03	0.49
FAETP (g DCB_{-Eq}./kWh)	13.10	2.47	4.02	287.90	21.20	1.65	63.90	14.70	20.90
GWP (g $CO_{2\text{-}Eq.}$/kWh)	455.78	420.00	490.00	1,078.84	7.79	3.70	88.91	12.35	58.51
HTP (g $DCB_{-Eq.}$/kWh)	54.30	38.00	39.50	294.86	111.43	6.15	205.47	61.81	208.50
MAETP (kg $DCB_{-Eq.}$/kWh)	37.42	0.50	0.90	1577.32	43.66	2.70	205.69	23.08	42.48
ODP (µg $R11_{-Eq.}$/kWh)	17.30	18.90	5.51	5.59	19.00	0.23	17.40	0.74	5.16
POCP (mg $C_2H_{4\text{-}Eq.}$/kWh)	83.80	34.40	66.60	285	5.55	2.04	67.00	6.97	131
TETP (g $DCB_{-Eq.}$/kWh)	1.70	0.15	0.22	1.75	0.74	0.19	1.12	1.81	4.26
Levelised cost of electricity (pence/kWh)	9.59	8.00	7.62	13.85	7.70	14.60	6.70	9.73	11.75
Capital cost (pence/kWh)	0.81	0.90	0.81	4.60	7.00	11.29	5.70	7.70	4.50
Fuel cost (pence/kWh)	6.51	4.90	4.53	3.60	0.50	0.00	0.00	0.00	5.30
Direct employment (person-yr/TWh)	47.70	62.00	326.88	191.00	87.00	782.35	653.00	368.00	385.79
Worker injuries (no. injuries/TWh)	0.53	0.54	2.10	4.50	0.59	14.59	4.84	2.30	2.98
Public support index (%)	5.60	34.00	14.50	-7.00	9.00	72.00	75.00	59.00	57.00
Diversity of fuel supply (no units)	1.00	1.00	0.04	0.86	0.85	1.00	1.00	1.00	0.96

[a] Data for the environmental indicators are sourced from Chapter 3, the economic from Chapter 4 and social from Chapter 5. Cost values for other electricity options are for 2030 as shale gas would be competing with future technologies. Values for environmental and social indicators were assumed to be the same as present values due to a lack of data on future trends of electricity technologies.
[b] For the acronyms, see the caption for Figure

Table 43: Current electricity mix and future scenarios[a].

Electricity source	**Current situation (2012) TWh**	**2030 (low shale penetration) TWh**	**2030 (high shale penetration) TWh**
Shale gas	0.00	4.60	28.74
Conventional gas	83.53	67.82	67.82
Liquefied natural gas	14.67	28.74	4.60
Coal	136.00	18.51	18.51
Nuclear	63.90	101.85	101.85
Hydro	5.28	8.51	8.51
Solar PV	1.19	3.00	3.00
Wind	19.58	104.68	104.68
Biomass	15.20	35.00	35.00

[a] Coal and gas carbon capture and storage are included in the 2030 mix, assuming an equal split between coal and gas.

Table 44: Sustainability indicators and their estimated values for the current electricity mix and future scenarios.

Indicators[a]	**Current mix (2012)**	**2030 (low shale gas penetration)**	**2030 (high shale gas penetration)**
ADP_e (mg Sb_{-Eq}./kWh)	0.08	0.24	0.27
ADP_f (MJ/kWh)	6.44	3.05	3.01
AP (g SO_2-$_{Eq.}$/kWh)	2.24	0.48	0.48
EP (g PO_4-$_{Eq.}$/kWh)	0.77	0.11	0.12
FAETP (g $DCB_{-Eq.}$/kWh)	118.84	17.56	18.04
GWP (kg $CO_{2\text{-}Eq.}$/kWh)	560	150	150
HTP (g DCB_{-Eq}./kWh)	143.64	92.84	93.64
MAETP (kg DCB_{-Eq}./kWh)	62.34	7.94	8.09
ODP (µg $R11_{-Eq}$./kWh)	12.41	13.67	14.30
POCP (mg $C_2H_{4\text{-}Eq.}$/kWh)	137.93	45.64	46.56
TETP (g $DCB_{-Eq.}$/kWh)	1.25	1.44	1.52
LCOE (pence/kWh)	9.72	10.99	10.95
Capital cost (pence/kWh)	3.22	5.27	5.27
Fuel cost (pence/kWh)	2.86	2.13	2.26
Direct employment (person-yr/TWh)[b]	175.30	233.04	214.96
Worker injuries (injuries/TWh) [b]	2.65	1.95	1.85
Public support index (%)	15.23	33.66	33.08
Diversity of fuel supply (-)	0.89	0.90	0.93

[a] For the acronyms, see the caption for Figure . Data for the environmental indicators sourced from Chapter 3, the economic from Chapter 4 and social from Chapter 5.
[b] Data not available for coal and gas carbon capture and storage.

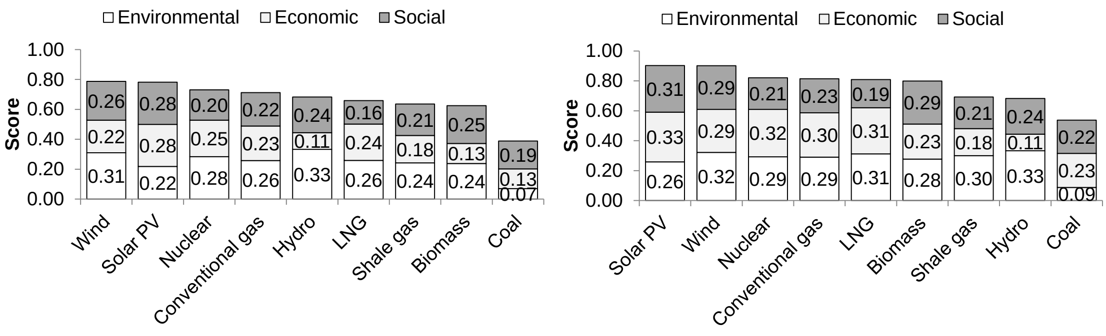
3. Results

This section first compares the overall sustainability of shale gas with the other electricity options. This includes a sensitivity analysis and the improvements in the life cycle of shale gas electricity that would be required to improve its overall ranking. This is followed by a comparison of the current electricity mix with the future scenarios and, finally, by the assessment of data quality.

3.1. Sustainability of shale gas electricity compared to other options

The results in Figure 34 indicate that if the environmental, economic and social aspects are equally important, the best options are wind and solar PV with scores of 0.79 and 0.78 (linear value function; LVF) and 0.90 (exponential; EVF) while the worst is coal with 0.39 (LVF) and 0.54 (EVF). Shale gas ranks seventh out of the nine options for both value functions scoring 0.64 and 0.69, respectively. The best and worst options are unaffected by the value function used but the order of some intermediate options changes. For example, hydroelectricity ranks fifth for the LVF and eighth for the EVF, while biomass ranks eighth for the LVF and sixth for the EVF. This is because the LVF does not take into account the magnitude of difference in the performance for different indicators (for these, see figures E1 and E2 in Appendix E). For instance, while biomass scores poorly for six out of 11 environmental indicators and for two out of three economic indicators, it is still much better (up to two orders of magnitude) than the worst option for each indicator (see Table 42). Thus, using the EVF, which takes this into account, is arguably more appropriate.

As can be seen in Figure 34, the environmental aspect contributes the most towards the overall score of shale gas (38-43%), followed by the social (30-33%) and finally the economic aspect (26-29%). Similar contributions are found for most of the other options. The exception is coal where the social aspect is dominant (41-48%) and the environmental has little influence (16-18%).



a) Linear value function b) Exponential value function

Figure 34: Ranking of the electricity options assuming equal importance for the sustainability aspects and indicators.

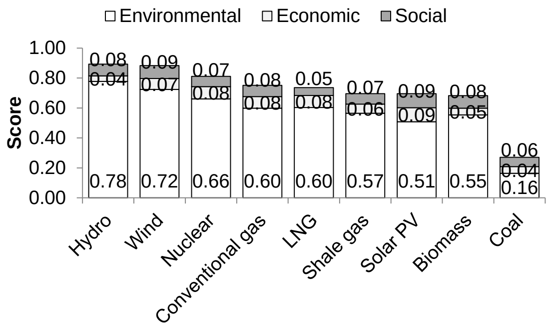
3.2. Sensitivity analysis

The sensitivity analysis explores how the ranking of the options changes when one of the three sustainability aspects is prioritised over the other two. In each case, the weighting of each aspect is changed until the ranking of the best or worst option changed. The equal importance of each sustainability indicator remains unchanged throughout. These results are discussed in turn in the next sections.

3.2.1. Environmental aspect

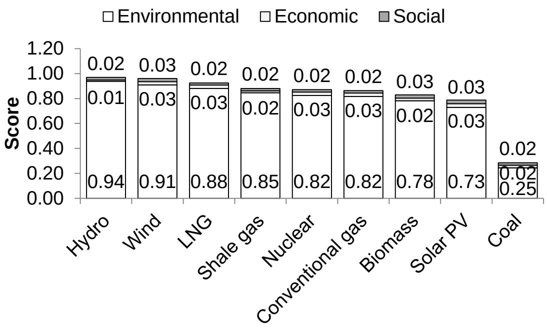
If the environmental aspect is assumed more important than the other two, wind and solar PV remain the best options until the weighting for the environmental aspect is seven times higher for the LVF (Figure 35a) and 31.5 times for the EVF (Figure 35b). At and above these weightings, hydroelectricity is the most sustainable option, followed closely by wind while solar PV drops to seventh and eighth place, respectively. Shale gas is ranked sixth (LVF) followed closely by solar PV and biomass and fourth (EVF) being only marginally better than nuclear and conventional gas.

When the importance of the environmental aspect is reduced by 2.8 times for the LVF, solar PV outranks wind as the best option and shale gas ranks sixth, marginally better than biomass and hydroelectricity (Figure 35c). For the EVF (Figure 35d), the importance of this aspect has to be 2.7 times lower than of the other two dimensions of sustainability for the rankings to change; solar PV is still the best option but hydroelectricity is now the least sustainable option, together with coal and followed closely by shale gas (ranks seventh).



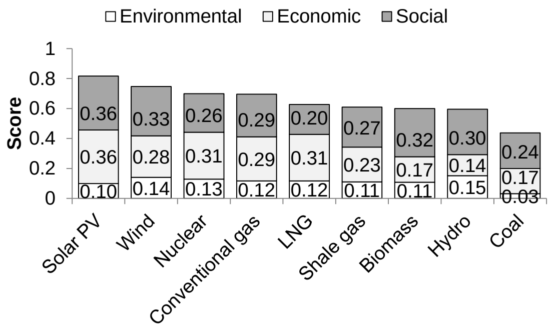
a) Seven times more important (LVF)

[Weights: environmental: 0.78, economic: 0.11, social: 0.11]



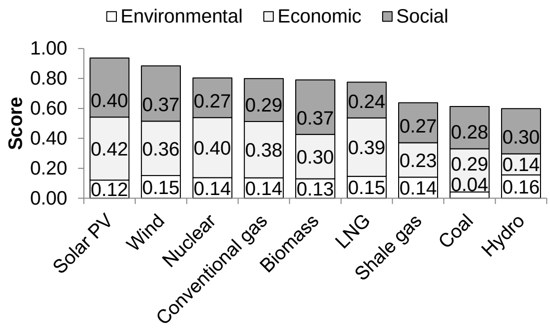
b) 31.5 times more important (EVF)

[Weights: environmental: 0.94, economic: 0.03, social: 0.03]



c) 2.8 times less important (LVF)

[Weights: environmental: 0.28, economic: 0.36, social: 0.36]



d) 2.7 times less important (EVF)

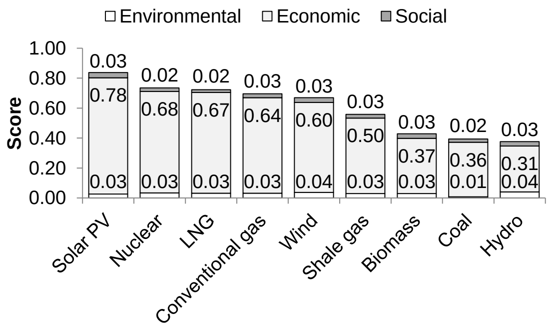
[Weights: environmental: 0.16, economic: 0.42, social: 0.42]

Figure 35: Ranking of the electricity options assuming different importance of the environmental aspect.

3.2.2. Economic aspect

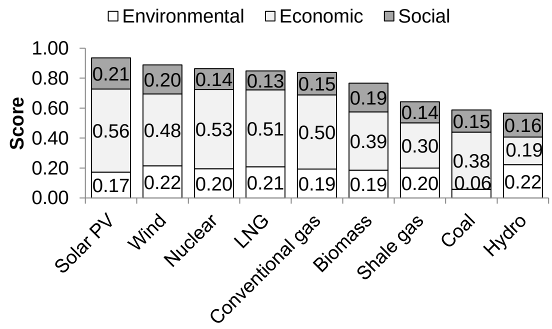
Wind and solar PV remain the best options until the weighting of the economic aspect is 23 times higher for the LVF (Figure 36a) and 2.5 times for the EVF (Figure 36b). At and above these weightings, solar PV is still the best option but hydroelectricity becomes the least sustainable option, followed closely by coal. It is interesting to note that for the LVF, wind drops fifth place (Figure 36a) because of its poor performance in levelised and capital costs. Shale gas ranks sixth for the LVF and the seventh for the EVF.

On the other hand, if the economic aspect is assumed to be the least important, the change in the rankings remains the same until it is 49.5 times less important (LVF). In this case, hydroelectricity (jointly with wind) is the most sustainable option (Figure 36c); shale gas is in seventh place. For the EVF, wind overtakes solar PV as the most sustainable option when the importance of the economic aspect is reduced by 4.5 times (Figure 36d).



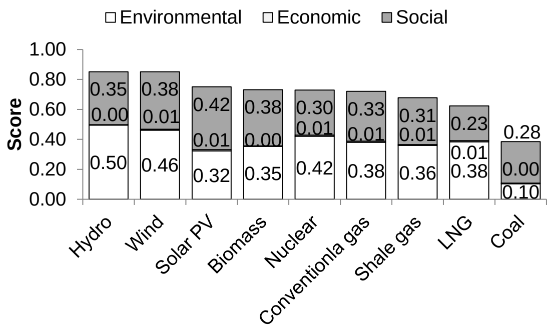
a) 23 times more important (LVF)

[Weights: environmental: 0.04, economic: 0.92, social: 0.04]



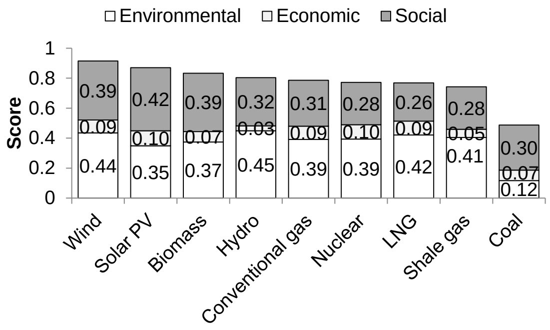
b) 2.5 times more important (EVF)

[Weights: environmental: 0.22, economic: 0.56, social: 0.22]



c) 49.5 times less important (LVF)

[Weights: environmental: 0.49, economic: 0.02, social: 0.49]



d) 4.5 times less important (EVF)

[Weights: environmental: 0.37, economic: 0.26, social: 0.37]

Figure 36: Ranking of the electricity options assuming different importance of the economic aspect.

3.2.3. Social aspect

The ranking of the options changes when the social aspect is 12.3 times more important than the other two for the LVF (Figure 37a) and 11 times for the EVF (Figure 37b), at which point LNG becomes the least sustainable option, narrowly behind coal. Shale gas ranks seventh for both value functions, following nuclear power (LVF); for the EVF, it is only marginally better than coal and LNG.

When the importance of the social aspect is reduced by 24.5 times for the EVF, LNG becomes the most sustainable option, being marginally better than wind, nuclear, solar PV and conventional gas (Figure 37c). Coal remains the least sustainable option and shale gas ranks seventh. For the LVF, there is no change in the rankings when the social aspect's importance is reduced.

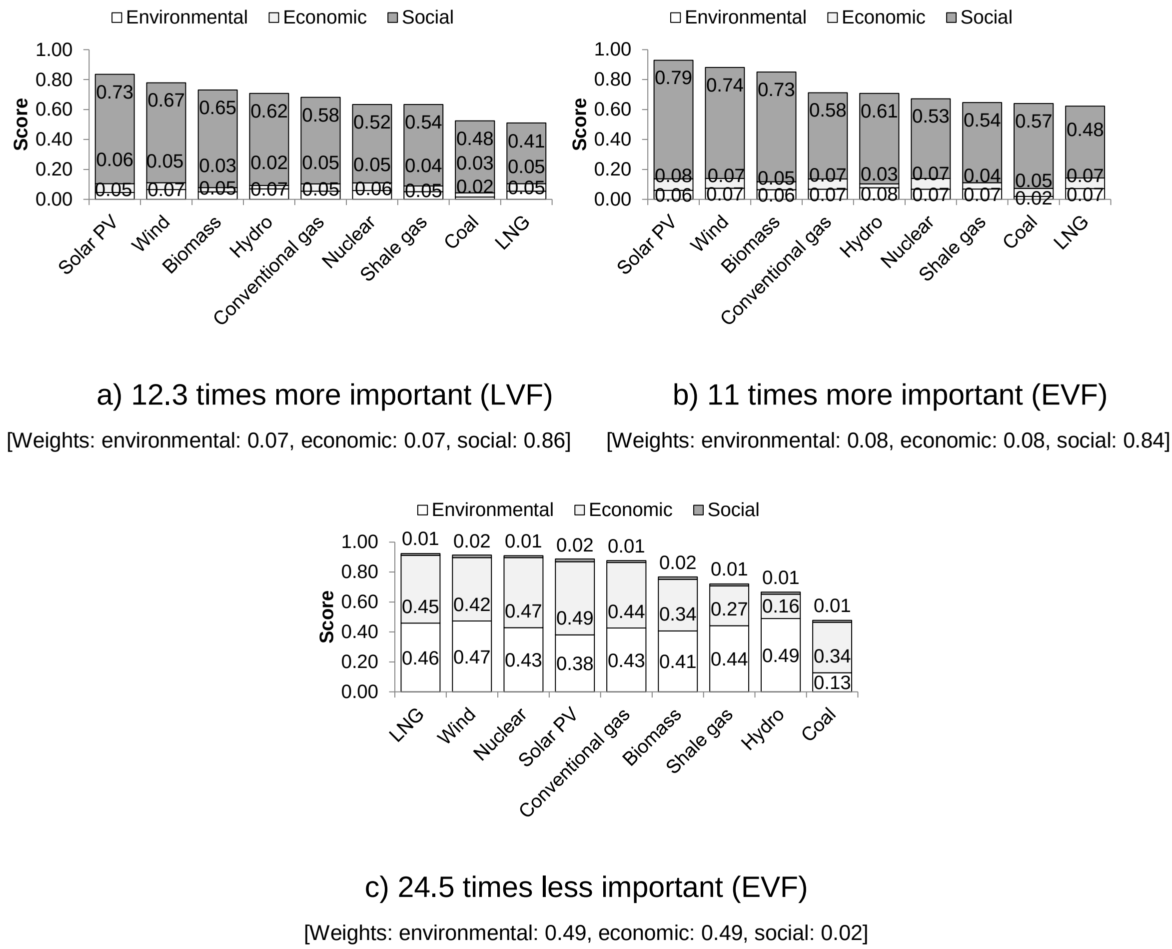


Figure 37: Ranking of the electricity options assuming different importance of the social aspect.

3.3. Robustness analysis

To assess the robustness of the results with respect to the MCDA method and the weightings used, the same analysis has been performed using direct weighting (DW) (Mustajoki and Hamalainen, 2000) as an alternative. This method is similar to SMART except that the weightings are inputted directly into the model, while in SMART they are calculated based on the assigned scores (see Section 2.1). Implementation of DW shows that the ranking and scores of the options remain the same for all the weightings considered in SMART in the previous section, thus validating the robustness of the results.

3.4. Changes needed for shale gas to become the most sustainable option

This section aims to determine what would be required for shale gas to become the most sustainable option amongst those considered in this study. First, multiple indicators are considered simultaneously for each sustainability aspect before looking at individual indicators.

3.4.1. Multiple sustainability indicators and aspects

Based on its performance in different sustainability aspects and indicators (Table 42) and not considering any improvements in performance, there are only two scenarios in which shale gas would become the top-ranking option (jointly with some others). These are as follows:

1. joint best with LNG and conventional gas if the capital cost is 1,000-10,000 times more important than the other economic indicators and, simultaneously, the economic aspect is 1,000 times more important than the other two aspects; and

2. joint best with conventional gas and nuclear if the importance of worker injuries is 1,000 times higher than of the other social indicators and, at the same time, the importance of the social aspect is 1,000 times greater than of the other two.

For the remaining indicators, shale gas can never be the best option unless its performance is improved considerably. For example, a 40-70% improvement is needed in all the indicators for shale gas to become the most sustainable option, jointly with wind and solar PV (Table 45). If the performance is improved in one sustainability aspect at a time, even larger improvements are needed. For the environmental aspect, a 100-fold reduction in the environmental impacts is required and this aspect has to be 3.8-23 times more important than the other two. For the economic aspect, a large reduction (50% to 20 times) in costs is needed, together with an increase in the importance of this aspect (up to 2.5 times) for shale gas to be the best option, together with solar PV. However, for greater reductions to all cost indicators (see Table 45), no changes in the importance of the economic aspect are needed. Improvements in the social indicators are only applicable to employment and public support, which must be improved by at least 16 and 13 times, respectively, for shale gas to emerge as the top option (Table 45). Thus, based on these results, it is highly unlikely that shale gas would be the most sustainable option among those assessed here.

Table 45: Improvements needed in different sustainability aspects and indicators for shale gas to be the most sustainable option.

Scenario	Improvements needed for shale gas to become the best option[a]	Notes[a]
Improvements in all indicators	Improvements of 45% (LVF) and 70% (EVF) in all indicators; equal weighting for all three aspects and indicators.	EVF: For a 40% improvement in all indicators and the economic aspect eight times more important, shale gas is the best option with solar PV.
Improvements in the environmental indicators only	100-fold reduction in all environmental impacts for both value functions; equal weighting for environmental indicators, but the environmental aspect must be 3.8 times more important than the economic and social aspects for the LVF and 23 times more important for the EVF.	Marginally better than wind assuming equal importance of the aspects. At a ten-fold reduction for both value functions, equal indicator weightings and 10,000 times greater importance of the environmental aspect, shale gas is marginally worse than the best option (hydro).
Improvements in the economic indicators only	Five times reduction in all cost indicators and no change in the importance of the aspects for it to be the best option together with solar PV (LVF). A 20-fold reduction in costs with the economic aspect 1.5 times more important to be marginally better than wind and solar PV (EVF).	LVF: At 50% reduction in all costs and economic aspect 2.5 times more important, shale gas is the best option, marginally better than solar PV. For the reduction in LCOE of 30% and zero fuel cost, shale gas is the best option together with wind assuming equal importance of all three sustainability aspects. EVF: For the 4.8 times lower LCOE and zero fuel cost, shale gas is the best option with wind and solar PV assuming equal importance of the sustainability aspects.
Improvements in the social indicators only	>13 times better PSI and >16 times greater DE for both value functions.	Improvements are only applicable to PSI and DE as shale gas is the best option for WI and scores the maximum for DFS.

[a] LVF: linear value function; EVF: exponential value function; LCOE: levelised cost of electricity; DE: direct employment; PSI: public support index; DFS: diversity of fuel supply.

3.4.2. Individual indicators

The results of the analysis when considering improvements to one indicator at a time together with its related aspect are shown in Table 46. As can be seen, the environmental impacts would need to be reduced by 9-329 times and their importance would have to be 10,000 times higher than of the other indicators, together with a 100 times greater importance of the environmental aspect relative to the other two. For the economic indicators, the LCOE needs to be reduced by 32%, with its importance increasing by 100 times, together with a similar increase in the importance of the economic aspect. As mentioned in the previous section, the capital cost does not need to be reduced, but if it is, then its importance must be increased by up to 10,000 times relative to the other indicators, along with a 100-10,000 times higher importance of the economic aspect (Table 46). The social indicators would need improvements similar in magnitude to those needed for the environmental indicators: direct employment by 16.4 times and public support by 13.6 times. The worker injuries do not need any reductions, but this indicator must be considered 1,000-10,000 times more important than the others, together with a similar increase in the importance of the social aspect over the other two.

Therefore, the above results suggest that shale gas is unlikely to be the best option in comparison to the other options considered in this work, as large improvements and considerable, sometimes extreme, increases in the importance of indicators and aspects are needed.

Table 46: Improvements needed in each indicator for shale gas to be the most sustainable option (changing one indicator at a time)[a].

Indicators	Current values	Improved values	Units	Increase in the indicator importance[b]	Increase in importance of related aspect[b]	Notes
ADP_e	0.68	0.007	mg Sb-Eq./kWh	10,000	100	Shale gas the best option, jointly with hydro
ADP_f	6.58	0.02	MJ/kWh	10,000	100	Shale gas the best option, jointly with hydro
AP	0.35	0.011 g	g SO_2-Eq./kWh	10,000	100	Shale gas the best option, jointly with hydro
EP	0.17	0.0045	g PO_4-Eq./kWh	10,000	100	Shale gas the best option, jointly with hydro
FAETP	13.10	1.4	g DCB-Eq./kWh	10,000	100	Shale gas the best option, jointly with hydro
GWP	455.78	3	g CO_2-Eq./kWh	10,000	100	Shale gas the best option, jointly with hydro
HTP	54.30	5.9	g DCB-Eq./kWh	10,000	100	Shale gas the best option, jointly with hydro
MAETP	37.42	0.49	kg DCB-Eq./kWh	10,000	1,000	Shale gas the best option, jointly with conventional gas and LNG
ODP	17.30	0.21	µg R11-Eq./kWh	10,000	100	Shale gas the best option, jointly with hydro
POCP	83.80	1.8	mg C_2H_4-Eq./kWh	10,000	100	Shale gas the best option, jointly with hydro
TETP	1.70	0.14	g DCB-Eq./kWh	10,000	100	Shale gas the best option, jointly with conventional gas
LCOE	9.59	6.50	pence/kWh	100 (LVF) 100 (EVF)	10 (LVF) 100 (EVF)	Shale gas the best option, jointly with solar PV
Capital cost	0.81	0.80 (LVF) 0.65 (EVF)	pence/kWh	1,000 (LVF) 10,000 (EVF)	100 (LVF) 10,000 (EVF)	Shale gas the best option, jointly with LNG

Table 46. (Continued)

Indicators	**Current values**	**Improved values**	**Units**	**Increase in the indicator importance**[b]	**Increase in importance of related aspect**[b]	**Notes**
Fuel cost	6.51	0	pence/kWh	10,000	10,000	Shale gas the best option, jointly with hydro, wind and solar PV
Direct employment	47.70	783	person-yr/TWh	100 (LVF) 1,000 (EVF)	100 (LVF) 10 (EVF)	Shale gas the best option, jointly with conventional gas
Worker injuries	0.53	0.53	injuries/TWh	1,000 (LVF) 10,000 (EVF)	1,000 (LVF) 1,000 (EVF)	Shale gas the best option, jointly with conventional gas
Public support index	5.60	76	%	1,000	1,000 (LVF) 100 (EVF)	Shale gas the best option, jointly with solar PV
Diversity of fuel supply	1.00	1.00	-	10,000	10,000	Shale gas the best option, jointly with conventional gas, hydro, wind and solar PV

[a] For the acronyms, see the caption in Figure . The values for the environmental indicators are the same for the linear value function (LVF) and exponential value function (EVF) as are the weightings required. Differences between LVF and EVF for the economic and social indicators are noted in the table where relevant.

3.5. Changes needed for shale gas to be comparable to different electricity options

The results in the previous section demonstrate that it is all but impossible for shale gas to be considered the most sustainable option. While this is informative, arguably, it is not necessary for shale gas to be *the* most sustainable option and it could still potentially be viable if it can compete with some of the other electricity options. Therefore, this section considers what would be needed to achieve that, starting with the other fossil fuels (conventional gas and LNG), followed by nuclear power and the renewables (hydroelectricity and biomass). Wind and solar PV are not considered as they are the most sustainable options based on the results discussed in sections 3.1 and 3.2, so that improvements needed for shale gas to compete with these two would be similar to those considered in the previous section. Note that coal is also not considered here either as shale gas is a more sustainable option for most scenarios discussed in the previous sections.

3.5.1. Comparison with conventional gas and LNG

As conventional gas and LNG rank higher than shale gas in the base case (Section 3.1), large reductions in the impacts of shale gas are needed, along with changes in the importance of the sustainability aspects. As indicated in Table 47, the environmental and social aspects need significant improvements while only a moderate reduction in costs is needed. This is because shale gas has much higher environmental impacts than conventional gas and LNG (Table 42) but has similar costs. For example, to be comparable with conventional gas, a 20% reduction in environmental impacts is necessary and the environmental aspect must be 13 times more important than the other two. Alternatively, an 80% reduction in impacts is needed if all three aspects are considered equally important. These results correspond to the LVF; for the EVF, a 100-fold reduction in environmental impacts is needed and the aspect must be three times more important. Similar results are found for LNG for the EVF. However, for the LVF, the required reductions in the environmental impacts are less drastic (40%) and no change in the importance of the aspects is needed (equal as the other two). By contrast, shale gas costs need only be reduced by 10-30% for it to compete with conventional gas and LNG. Arguably, this may be achievable through economies of scale.

When individual indicators are considered, reductions are needed in nine out of 11 environmental impacts for it to compete with conventional gas and in eight for LNG. For these indicators a small reduction (6-36%) is needed in indicators where shale gas is marginally worse than the other (Table 48). However, for the indicators were shale gas is significantly worse, 2.8-76.4 times reductions are needed. In both cases a large increase in the importance of indicators and the environmental aspect would be needed (100-1,000 times). No reductions are needed in acidification and ozone layer depletion relative to conventional gas and the required increase in their importance is also smaller than for the other indicators (ten-fold). With respect to LNG, three environmental impacts do not need improving: fossil fuel resource depletion, acidification and global warming potential; however, the importance of the latter must increase by 100 times and that of the other two by ten and three times, respectively.

Improvements are also needed in in social and economic indicators: 18-31% for levelised and fuel costs and 32% to 6.5-fold for direct employment and public support index (Table 48), along with large increases in the importance of these indicators (100-1,000) and their related sustainability aspects (10-100 times). For the remaining indicators, no improvements are needed, but unlike the environmental indicators, large increases in aspect/indicator importance are needed for fuel costs and diversity of fuel supply (100-10,000 times). This is due to either a marginal or no difference between the values of shale gas and the other two gas options for these indicators. However, the workers injuries requires a smaller increase in the importance of the indicator and the social aspect (2-100 times), as shale gas scores better in this indicator than the other gas options.

Table 47: Improvements needed for each sustainability aspect for shale gas to become comparable to conventional gas and LNG.

Sustainability aspect	**Conventional gas**		**LNG**	
	Linear value function	*Exponential value function*	*Linear value function*	*Exponential value function*
Environmental	20% reduction in environmental impacts and aspect 13 times more important or 80% reduction in impacts and equal importance as the other two aspects.	100-fold reduction in environmental impacts and aspect three times more important.	20% reduction in environmental impacts and aspect 13 times more important or 40% reduction in impacts and equal importance as the other two aspects.	100-fold reduction in environmental impacts and aspect 5.2 times more important.
Economic	30% reduction in costs and equal importance as the other two aspects.	25% reduction in costs and equal importance as the other two aspects.	10% reduction in costs and equal importance as the other two aspects.	20% reduction in costs and equal importance as the other two aspects.
Social[a]	Five-fold increase in DE and PSI and aspect 4.7 times more important or ten-fold increase in DE and PSI and equal importance as the other two aspects.	Five-fold increase in DE and PSI and aspect 4.7 times more important.	Five-fold increase in DE and PSI and equal importance as the other two aspects.	Ten-fold increase in DE and PSI and equal importance as the other two aspects.

[a] DE: direct employment; PSI: public support index.

Table 48: Improvements needed for each indicator for shale gas to be comparable to conventional gas and LNG.

Indicators[a]	**Units**	**Shale gas**	**Conventional gas**			**LNG**		
		Current values	*Improved values*	*Increase in importance of indicator*	*Increase in importance of related aspect*	*Improved values*	*Increase in importance of indicator*[b]	*Increase in importance of related aspect*[b]
ADP_e	mg $Sb_{-Eq.}$/kWh	0.68	0.10	1,000	100	0.20	1,000	100
ADP_f	MJ/kWh	6.58	6.20	1,000	100	6.58	10	5
AP	g $SO_{2\text{-}Eq.}$/kWh	0.35	0.35	10	2	0.35	3	-
EP	g $PO_{4\text{-}Eq.}$/kWh	0.17	0.02	1,000	100	0.02	1,000	100
FAETP	g $DCB_{-Eq.}$/kWh	13.10	1.40	10,000	100	1.40	10,000	100
GWP	g $CO_{2\text{-}Eq.}$/kWh	455.78	400.00	1,000	100	455.78	100	100
HTP	g $DCB_{-Eq.}$/kWh	54.30	35.00	1,000	100	35.00	1,000	100
MAETP	kg $DCB_{-Eq.}$/kWh	37.42	0.49	100,000	1,000	0.49	100,000	1,000
ODP	µg $R11_{-Eq.}$/kWh	17.30	17.30	10	10	5.90	1,000	100
POCP	mg $C_2H_{4\text{-}Eq.}$/kWh	83.80	30.00	1,000	100	65.00	1,000	100
TETP	g $DCB_{-Eq.}$/kWh	1.70	0.14	10,000	100	0.20	1,000	100
LCOE	pence/kWh	9.59	7.90	100	10	7.61	100	10
Capital cost	pence/kWh	0.81	0.81	1,000	100	0.81	1,000	100
Fuel cost	pence/kWh	6.51	4.80	1,000	100	4.50	1,000	100
Direct employment	person-yr/TWh	47.70	63.00	100	100	327.00	100	100
Worker injuries	injuries/TWh	0.42	0.42	100	100	0.42	10 (LVF) 100 (EVF)	2 (LVF) 100 (EVF)
Public support index	%	5.60	35.00	100	100	15.00	100	100
Diversity of fuel supply	-	1.00	1.00	10,000	10,000	1.00	1.5 (LVF) 5 (EVF)	1

[a] For the acronyms, see the caption in Figure .
[b] LVF: linear value function; EVF: exponential value function.

3.5.2. Comparison with nuclear power

As nuclear power ranks significantly better than shale gas in the base case (Figure 34), significant improvements and increases in the importance of the sustainability aspects and indicators are needed if shale gas is to be comparable. The magnitude of the improvements and increases in importance are similar to those needed for it to compete with conventional gas as nuclear power has a similar ranking to it (Figure 34). As shown in Table 49, the environmental and social aspects need the largest improvements (up to 100 times) while the required cost reductions are much smaller (25-40%).

When the individual indicators are targeted (Table 50), improvements are needed in seven out of the 11 environmental indicators. For these, 89% to 91-fold reductions are needed along with large increases in aspect/indicator importance (100-10,000 times). For the remaining four (human, freshwater and marine toxicity and ozone layer depletion), no reductions are needed and smaller increases in aspect/indicator importance are needed (5-1,000 times). For the economic and social indicators, improvements are needed in the levelised cost of electricity, fuel cost, direct employment and public support (Table 50). The levelised costs of electricity needs a 21% reduction and 10-100 times increase in aspect/indicator importance, while the fuel cost must be reduced 16-fold and the importance of the aspect/indicator increased by 100-1,000 times. However, the capital cost of nuclear power is considerably higher than that of shale gas and, as a result, no reductions in capital cost are needed along with a much smaller increase in the aspect/indicator importance (2-100 times). A 72-79% increase in direct employment and public support are required, along with 100-fold increases in the aspect and indicator importance (Table 50). No improvements in worker injuries and diversity of fuel supply are necessary for shale gas to compete with nuclear power but the aspect/indicator importance must be 3-100 times higher (Table 50).

Table 49: Improvements needed for each sustainability aspect for shale gas to become comparable to nuclear power.

Sustainability aspect	**Nuclear power**	
	Linear value function	*Exponential value function*
Environmental	Five-fold reduction in environmental impacts and aspect 1.8 times more important or 100-fold reduction in environmental impacts and equal importance as the other two aspects.	100-fold reduction in environmental impacts and aspect 3.3 times more important.
Economic	30% reduction in costs and aspect three times more important or 40% reduction in costs and equal importance as the other two aspects.	25% reduction in costs and equal importance as the other two aspects.
Social[a]	Ten-fold increase in DE and PSI and aspect 1.3 times more important or 13-fold increase in DE and PSI and equal importance as the other two aspects.	Ten-fold increase in DE and PSI and aspect 1.5 times more important or 17-fold increase in DE and PSI and equal importance as the other two aspects.

[a] DE: direct employment; PSI: public support index.

Table 50: Improvements needed for each indicator for shale gas to be comparable to nuclear power.

Indicators[a]	Units	Current values	Improved values	Increase in importance of the indicator[b]	Increase in importance of related aspect[b]
ADP_e	mg $Sb_{-Eq.}$/kWh	0.68	0.05	1,000	100
ADP_f	MJ/kWh	6.58	0.08	1,000	100
AP	g $SO_{2-Eq.}$/kWh	0.35	0.04	1,000	100
EP	g $PO_{4-Eq.}$/kWh	0.17	0.02	1,000	100
FAETP	g $DCB_{-Eq.}$/kWh	13.10	13.10	100	10
GWP	g $CO_{2-Eq.}$/kWh	455.78	5.00	1,000	100
HTP	g $DCB_{-Eq.}$/kWh	54.30	54.30	10	10
MAETP	kg $DCB_{-Eq.}$/kWh	37.42	37.42	1,000	100
ODP	µg $R11_{-Eq.}$/kWh	17.30	17.30	100	5
POCP	mg $C_2H_{4-Eq.}$/kWh	83.80	4.00	1,000	100
TETP	g $DCB_{-Eq.}$/kWh	1.70	0.73	10,000	100
LCOE	pence/kWh	9.59	7.60	100	10
Capital cost	pence/kWh	0.81	0.81	3 (LVF) 100 (EVF)	2 (LVF) 10 (EVF)
Fuel cost	pence/kWh	6.51	0.40	1,000	100
Direct employment	person-yr/TWh	47.70	88.00	100	100
Worker injuries	injuries/TWh	0.42	0.42	100	100
Public support index	%	5.60	10.00	100	100
Diversity of fuel supply	-	1.00	1.00	10 (LVF) 5 (EVF)	3 (LVF) 5 (EVF)

[a] For the acronyms, see the caption in Figure .
[b] LVF: linear value function; EVF: exponential value function.

3.5.3. Comparison with hydroelectricity and biomass

Hydroelectricity and biomass are the bottom ranking renewables assuming equal importance of all aspects and indicators. Shale gas outranks the former for the EVF and the latter for the LVF (Figure 34). Therefore, improvements to compete with hydroelectricity are only applicable to the LVF and the EVF for biomass. As both options are closer in ranking to shale gas than conventional gas, LNG and nuclear power, smaller improvements and increases in the importance of aspects and indicators are needed as shown in Table 51. The social aspect needs the largest improvement (8-10 times), followed by the environmental (20-50%) and economic (20%) aspects.

However, significant improvements (9-329 times) are needed in all environmental indicators for shale gas to compete with hydroelectricity (Table 52). This is because the latter is the best option for nine out of 11 environmental indicators and the second and third best for the other two. A 100-10,000 times increase in aspect/indicator importance is also needed. Relative to biomass, four impacts (depletion of elemental resources and fossil fuel resources, global warming and ozone layer depletion) need reducing by 3.5-11.4 times, along with 100-10,000 times increase in aspect/indicator importance (Table 52). For the remaining seven indicators, no improvements are needed but the importance of the aspects and indicators must increase by 2-100 times.

For the economic indicators, shale gas has lower levelised and capital cost than both renewables, but its fuel cost is higher. As a result, no reductions in levelised and capital cost are needed but an increase in aspect/indicator importance of up to 1,000 times is required (Table 52). On the other hand, fuel cost must be reduced to zero and the importance of the aspect/indicator increase 10,000-fold for it to compete with hydroelectricity while a 20% reduction and 100-fold increase in importance is needed for it to compete with biomass.

Shale gas scores much better than both renewables in worker injuries so no improvements in this indicator are needed, but up to 50-fold increase in aspect/indicator importance is required. Direct employment needs to be improved by 16.4-fold and public support needs to be 13 times higher to compete with hydroelectricity, along with a 100-fold increase in aspect/indicator importance (Table 52). As both shale gas and hydroelectricity have the maximum score in diversity of fuel supply, no improvement is needed in this indicator, but aspect/indicator importance must be increased 10,000-fold. To compete with biomass, an eight-fold increase in direct employment and 10.4 times increase in public support are needed, together with 100-1,000 times increase in aspect/indicator importance. For the diversity of fuel supply, biomass scores lower than shale gas and hence no improvements are needed, but a five to 100 times increase in aspect/indicator importance is necessary.

Table 51: Improvements needed for each sustainability aspect for shale gas to become comparable to hydroelectricity and biomass electricity.

Sustainability aspect	**Hydro**	**Biomass**
Environmental	50% reduction in environmental impacts and equal importance as the other two aspects (for linear value function only).	20% reduction in environmental impacts and aspect 3.9 times more important (for exponential value function only).
Economic	20% reduction in costs and equal importance as the other two aspects (for linear value function only).	20% reduction in costs and equal importance as the other two aspects (for exponential value function only).
Social[a]	Eight-fold increase in DE and PSI and equal importance as the other two aspects (for linear value function only).	Ten-fold increase in DE and PSI and equal importance as the other two aspects (for exponential value function only).

[a] DE: direct employment; PSI: public support index.

Table 52: Improvements needed for each indicator for shale gas to be comparable to hydroelectricity and biomass.

Indicators[a]	Units	Shale gas	Hydro			Biomass		
		Current values	*Improved values[b]*	*Increase in importance of indicator*	*Increase in importance of related aspect*	*Improved values[c]*	*Increase in importance of indicator*	*Increase in importance of related aspect*
ADP_e	mg $Sb_{-Eq.}$/kWh	0.68	0.01	10,000	100	0.13	10,000	100
ADP_f	MJ/kWh	6.58	0.02	10,000	100	0.60	10,000	100
AP	g $SO_{2\text{-}Eq.}$/kWh	0.35	0.01	10,000	100	0.35	10	10
EP	g $PO_{4\text{-}Eq.}$/kWh	0.17	0.02	1,000	100	0.17	5	5
FAETP	g $DCB_{-Eq.}$/kWh	13.10	1.40	10,000	100	13.10	100	100
GWP	g $CO_{2\text{-}Eq.}$/kWh	455.78	3.00	10,000	100	40.00	10,000	100
HTP	g $DCB_{-Eq.}$/kWh	54.30	5.90	10,000	100	54.30	10	3
MAETP	kg $DCB_{-Eq.}$/kWh	37.42	0.50	100,000	1,000	37.42	100	10
ODP	µg $R11_{-Eq.}$/kWh	17.30	0.21	10,000	100	5.00	10,000	100
POCP	mg $C_2H_{4\text{-}Eq.}$/kWh	83.80	1.80	10,000	100	83.80	10	6
TETP	g $DCB_{-Eq.}$/kWh	1.70	0.18	10,000	100	1.70	2	3
LCOE	pence/kWh	9.59	9.59	5	5	9.59	5	2
Capital cost	pence/kWh	0.81	0.81	2	1	0.81	1,000	100
Fuel cost	pence/kWh	6.51	0.00	10,000	10,000	5.20	100	100
Direct employment	person-yr/TWh	47.70	783.00	100	100	386.00	1,000	100
Worker injuries	injuries/TWh	0.42	0.42	2	1	0.42	50	5
Public support index	%	5.60	73.00	100	100	58.00	1,000	100
Diversity of fuel supply	-	1.00	1.00	10,000	10,000	1.00	100	5

[a] For the acronyms, see the caption in Figure .
[b] For linear value function only.
[c] For exponential value function only.

3.6. Influence on the sustainability of grid electricity

The results in Table 53 suggest that, assuming equal importance of all the sustainability aspects and indicators, the electricity mix with low shale gas penetration is considerably more sustainable than for the higher contribution, with the respective sustainability scores of 0.74 and 0.44. This is to be expected because, as discussed in the previous sections, shale gas generally scores poorly in various impacts, including: global warming, fuel cost and public support (see Table 42). Only when 10,000 times lower importance is placed on the environmental aspect do the two electricity mixes become comparable (Table 53).

When the individual indicators are considered, in order for the high penetration mix to become comparable with the low, improvements are necessary in all but two environmental impacts as well as in capital and fuel costs, employment and public support. As can be seen in Table 54, the improvements needed range from 2-16%. However, no changes to aspect importance are required (except for the diversity of fuel supply) but the importance assigned to each indicator must increase five to 80-fold.

It can also be seen in Table 53 that both 2030 electricity mixes are more sustainable than the present mix, assuming equal importance of all three sustainability aspects. This is not because of shale gas but is instead due to the large drop in the contribution from coal and the growth in renewables. The current mix is only better if the economic aspect is 3.9 times more important than the other two. This is due to the average levelised cost of current fossil fuel electricity being lower than that of renewables, making 2030 electricity more expensive. For the current mix to be comparable to the 2030 mixes, improvements must be made to all social indicators (6% to 2.2 times), eight environmental impacts (36% to 7.9-times) and fuel cost (26%); see Table 54. An increase in the importance of the indicators and their related aspects (up to 1,000-fold) is also required.

Table 53: Sustainability scores of the 2030 mixes in comparison with the current mix assuming differing importance of sustainability aspects.

Importance of aspects	**Current situation (2012)**	**2030 (low penetration of shale gas)[a]**	**2030 (high penetration of shale gas)[a]**
Equal importance	-[b]	0.74	0.44
Environmental aspect 10,000 times less important than economic and social	-[b]	0.67	0.67
Equal importance	0.39	0.69	0.63
Economic aspect 3.9 times more important than the other two	0.53	0.52	0.46

[a] Low penetration: 1% contribution to the electricity mix. High penetration: 8% contribution.
[b] No values as the comparison is between future electricity mixes only.

Table 54: Improvements needed for each indicator for the 2030 high shale mix and present mix to become comparable to the low shale mix[a].

Indicator[b]	**Units**	**High shale gas contribution**				**Current situation (2012)**			
		Current values	*Improved values*	*Increase in importance of indicator*	*Increase in importance of related aspect*	*Current values*	*Improved values*	*Increase in importance of indicator*	*Increase in importance of related aspect*
ADP_e	mg $Sb_{-Eq.}$/kWh	0.27	0.24	11	1	0.08	0.08	20	1
ADP_f	MJ/kWh	3.01	3.01	15	1	6.44	2.90	20	1
AP	g $SO_{2\text{-}Eq.}$/kWh	0.48	0.46	11	1	2.24	0.46	15	1
EP	g $PO_{4\text{-}Eq.}$/kWh	0.12	0.10	11	1	0.77	0.10	30	1
FAETP	g $DCB_{-Eq.}$/kWh	18.04	17.50	11	1	118.84	17.50	1,000	3
GWP	g $CO_{2\text{-}Eq.}$/kWh	150	150	15	1	560	150	1,000	1
HTP	g $DCB_{-Eq.}$/kWh	93.64	92.00	11	1	143.64	92.00	100	1
MAETP	kg DCB-$_{Eq.}$/kWh	8.09	7.93	11	1	62.34	7.93	1,000	5
ODP	µg $R11_{-Eq.}$/kWh	14.30	13.60	11	1	12.41	12.41	30	1
POCP	mg $C_2H_{4\text{-}Eq.}$/kWh	46.56	45.00	11	1	137.93	45.00	100	1
TETP	g $DCB_{-Eq.}$/kWh	1.52	1.43	11	1	1.25	1.25	30	1
LCOE	pence/kWh	10.95	10.95	22	1	9.72	9.72	2	3.5
Capital cost	pence/kWh	5.27	5.26	5	1	3.22	3.22	2	3.5
Fuel cost	pence/kWh	2.26	2.12	10	1	2.86	2.12	2	3
Direct employment	person-yr/TWh	214.96	234.00	5	1	175.30	234	20	10
Worker injuries	injuries/TWh	1.85	1.85	10	1	2.65	1.84	15	3
Public support index	%	33.08	34.00	5	1	15.23	34.00	20	20
Diversity of fuel supply	-	0.93	0.93	80	8	0.89	0.94	80	30

[a] Results shown are for the linear value function only for illustration as the choice of the value function does not affect the ranking.
[b] For the acronyms, see the caption in Figure .

3.7. Data quality

As discussed in Section 2.3, the quality of the data underlying this sustainability assessment has been evaluated according to six criteria considered in the pedigree matrix (see Table E2 in Appendix E). Overall, the data quality is estimated to be 'medium' for the environmental and economic assessment, 'high' for the social sustainability assessment and 'medium' for the 2030 electricity mix (Table 55). This would suggest that the results are valid, but further improvements to the data used would increase their robustness.

Some data sources were of poor quality, in particular the sample size for the LCC data and geographical correlation for the LCA (Table E3 in Appendix E). This is because the data used to estimate the cost of producing shale gas in the UK is based on reports which estimate the cost of establishing a UK shale industry. Similarly, as the UK has no shale gas industry but only exploration wells, US data for material and process requirements were used to model shale gas wells. Despite this, the overall data quality is 'medium' to 'high'. Also, the quality of the literature data scored well in comparison to the Ecoinvent data used (Table E4 in Appendix E).

Table 55: Data quality assessment results using the pedigree matrix method.

	Environmental data (LCA)[a]	**Economic data (LCC)[a]**	**Social data (SSA)[a]**	**2030 electricity mix**
Reliability	3.06	2.17	1.36	1.88
Completeness	1.25	1.00	1.04	1.00
Temporal correlation	1.26	1.08	1.44	1.75
Geographical correlation	1.8	1.00	2.37	1.47
Technological correlation	1.75	1.83	1.52	1.03
Sample size	4.7	5.00	3.71	5.00
Overall data quality	13.82 (Medium)	12.08 (Medium)	11.44 (High)	12.13 (Medium)

[a] LCA: life cycle assessment; LCC: life cycle costing; SSA: social sustainability assessment.

4. Conclusions

The results of this study show that, assuming equal importance of the environmental, economic and social aspects, shale gas ranks seventh out of the nine electricity options considered. In this case, wind and solar PV are the most sustainable and coal the worst option. If the environmental aspect is the most important, hydroelectricity becomes the best option, with shale gas ranking fourth to seventh, depending on the value function used. For high importance of the economic aspect, solar PV is the best option while coal and hydroelectricity represent the least sustainable options; shale gas ranks sixth or seventh. Finally, if the social aspect is considered the most important, solar PV is the most sustainable option with coal and LNG being the worst options; shale gas is in sixth to eighth place. Therefore, while overall not the worst, shale gas is not one of the better options either.

Despite this, it is possible to arrive at an outcome where shale gas is the best option by altering the importance placed on the indicators and aspects as well as by improving its performance in different indicators. However, these are significant and unrealistic. For example, if the importance of the capital cost and the economic aspect is 10,000 higher, shale gas becomes the best option (with conventional gas and LNG). Similarly, when the importance of worker injuries and the social aspect is increased 10,000-fold, shale gas emerges as the most sustainable option along with conventional gas. However, for the other indicators large improvements would be needed, in combination with significant increases in the importance placed on the sustainability aspects and indicators. For the environmental aspect, improvements in impacts can lead to shale gas becoming the best option (jointly with hydro) but only at a 9-329 fold reduction and in combination with significant increases in their importance (100-10,000 times). For the economic aspect and indicators, the levelised cost must be reduced by a minimum of 32% and their importance must be increased by 10-100 times. Alternatively the fuel cost must be zero and its importance increased by 10,000-fold for shale to be the most sustainable option, together with hydroelectricity, wind and solar PV. Large increases in the importance (100-1,000 times) are also required for public support and employment, together with improvements in their values (13.6 and 16.4 times, respectively). No improvements are necessary for diversity of fuel supply but the importance of this indicator and the social aspect must increase 10,000-fold and even then, it is level with conventional gas, hydroelectricity, wind and solar PV as the most sustainable options.

For shale gas to compare with conventional gas, LNG and nuclear power, large improvements in its performance are needed, along with significant increases in the importance of the sustainability aspects and indicators. For example, to compete with nuclear power, an 89% to 91-fold reduction in environmental impacts is needed and their importance must be increased by 100-1,000 times. However, this is only applicable for seven out of the 11 indicators. For the remaining four, no improvements are needed as shale gas has lower impacts, but a 5-1,000 times increase in their importance is necessary. In some scenarios, shale gas is already more sustainable than hydroelectricity and biomass but in others, large improvements to environmental and social impacts would be needed.

The results also suggest that a future electricity mix with a lower penetration of shale gas is more sustainable than one with the higher contribution, assuming the sustainability aspects are of equal importance. If higher importance is placed on the economic or social aspects, the high shale gas mix outranks the low due to the relatively low cost of shale gas compared to renewables.

Although the quality of the data used in this study is considered ‘medium’ to ‘high’, some data are derived from non-UK sources, which is one of the limitations of this work. If or when the exploitation of shale gas starts in the UK, using actual field data would help to refine the findings of this research. A further limitation is the limited number of economic and social indicators considered and future work should consider others, such as tax revenue, contribution to gross domestic product, community benefits, local employment, noise and traffic, to name a few. Another limitation is the lack of stakeholder input into the decision analysis, particularly their preferences for different sustainability aspects and indicators. Despite this, the study shows that the overall conclusions are robust to changes in preferences.

References

Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Roland Hischier, Nemecek, T., Rebitzer, G., Spielmann, M. and Wernet, G. **2007**. *Overview and methodology: Data v2.0 (2007)*. *The ecoinvent Centre*. Zurich, CH. Retrieved from: http://www.ecoinvent.org/database/older-versions/ecoinvent-version-2/methodology-of-ecoinvent-2/methodology-of-ecoinvent-2.html.

Edwards, W. **1977**. How to use multiattribute utility measurement for social decisionmaking. *IEEE Transactions on Systems, Man and Cybernetics*, SMC-7, 326-339.

Lewis, C., Speirs, J. and MacSweeney, R. **2014**. *Getting ready for UK shale gas: Supply chain and skills requirements and opportunities*. *United Kingdon Onshore Oil and Gas and Ernst and Young*. London. Retrieved from.

Mustajoki, J. and Hamalainen, R. P. **2000**. Web-HIPRE: Global decision support by value tree and AHP analysis. *Information Systems and Operational Research (INFOR)*, 38, 208-220.

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O. and Wernet, G. **2013**. *Overview and methodology: Data quality guideline for ecoinvent database version 3 (final)*. *The ecoinvent Centre*. Zurich, CH. Retrieved from: https://www.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf.

Chapter 7. Conclusions and recommendations

The work presented in this thesis has analysed the impacts of shale gas on the UK electricity market, focusing on its use for electricity generation. The life cycle environmental, economic and social sustainability of shale gas electricity have been conducted and used to assess the overall sustainability. The impact of shale gas on the sustainability of the UK electric mix has also been assessed by comparing future scenarios with the current (2012) mix. As far as the author is aware, this is the most comprehensive and extensive sustainability assessment of shale gas production and use for electricity generation in the UK. The methodology outlined in Chapter 1 details the procedures conducted for the sustainability assessment. The environmental sustainability has been analysed using life cycle assessment (LCA), in which 11 indicators are used to assess the environmental impacts of shale gas electricity and to compare it to other options. The indicators consider impacts to resource depletion, toxicity, climate change, acidification, eutrophication, ozone depletion and photochemical creation. The economic sustainability has been analysed using life cycle costing (LCC), which allows for the economic viability and competitiveness of shale gas to be determined. The social sustainability has been assessed using fourteen indicators which assess impacts to the community as a result of shale gas and shale gas electricity. The results of the LCA, LCC and social sustainability assessment have been integrated in a multi-criteria decision analysis (MCDA) to evaluate the overall sustainability of shale gas electricity and rank it against the following electricity options: conventional gas, liquefied natural gas (LNG), coal, nuclear power, hydroelectricity, solar photovoltaics (PV), wind and biomass, based on sustainability as defined in this study. Finally, a data quality assessment has been conducted to grade the quality of the data used in the assessment.

The results are presented in four papers (chapters 3 to 6) in addition to an overview of the sustainability of shale gas based on a literature review (Chapter 2). The research objectives specified in Chapter 1 have been achieved through the above papers as follows:

- the environmental, economic and social sustainability of shale gas and shale gas electricity have been assessed;
- the life cycle sustainability of shale gas has been compared with other options;
- future scenarios have been developed to assess the impact of shale gas on the sustainability of the UK electric gird;

- areas for improvement in the shale gas electricity life cycle have been identified; and
- recommendations have been made based on the improvements identified.

The main conclusions of this work are summarised below, followed by the recommendations drawn from the conclusions and recommendations for future work.

1. Conclusions

1.1. Life cycle sustainability assessment of shale gas electricity

1.1.1. Environmental impacts

- Shale gas has higher environmental impacts than conventional gas and liquefied natural gas (LNG) for nine and eight out of 11 impact categories, respectively, but has lower impacts for nine out of 11 impact categories than coal;
- shale gas has higher elemental abiotic resource depletion than conventional gas and LNG, as well as the other electricity options with the exception of solar PV. The elemental abiotic resource depletion of shale gas is 2.6-68 times higher than the other options, but is 16 times lower than solar PV;
- the main cause of the high resource depletion is the drilling fluid used to drill the well;
- shale gas has higher fossil fuel abiotic resource depletion than conventional gas (5%) and all the non-fossil fuel options (6.6 to over 6,600 times), but the fossil fuel depletion is lower than LNG (12%) and coal (1.8 times);
- the main cause of fossil fuel depletion is the burning of natural gas in the power plant to generate electricity;
- the acidification potential of shale gas is lower than conventional gas and LNG (4-8.5 times lower, respectively), as well as biomass, coal (highest) and solar PV, but is higher than nuclear power, hydroelectricity and wind;
- the main cause of acidification is the burning of gas in the power plant;
- the eutrophication potential of shale gas is higher than conventional gas, LNG, nuclear, hydroelectricity and wind (2.8-17 times higher) but is lower than coal, solar PV and biomass, by 41% to 11 times, out of which coal has the highest eutrophication potential;

- the disposal of drilling waste contributes the most towards eutrophication in the shale gas electricity life cycle;

- the freshwater aquatic ecotoxicity potential of shale gas is five higher than conventional gas, three times higher than LNG and eight times higher than hydroelectricity, but it is lower than the other options, out of which coal is the highest;

- the drilling waste disposal is the main contributor towards the freshwater toxicity, because of toxic chemicals used in the drilling fluid;

- shale gas has a global warming potential higher than the non-fossil fuel options and conventional gas, similar to what was found for fossil fuel depletion. The global warming potential of LNG is 7% higher and coal is 2.3 times higher;

- the combustion of gas in the power plant is the main contributor towards the global warming potential;

- shale gas has a human toxicity potential higher than conventional gas, LNG and hydroelectricity, but is 15% to 5.5 times lower than the other options, out of which coal is the worst;

- the disposal of drilling waste is the main cause of human toxicity because of the toxic chemicals used in the drilling fluid;

- the marine aquatic ecotoxicity potential of shale gas is higher than conventional gas, LNG, hydroelectricity and wind, but is 14% to 42 times lower than the other options, out of which coal is the worst;

- the disposal of drilling waste, like what was found for the freshwater and human toxicity, is the main contributor towards this impact;

- shale gas has ozone depletion potential higher than all the options, except for conventional gas (highest), nuclear power and solar PV, which are 9.8%, 9.6% and 0.7% higher, respectively;

- the transport and distribution of gas is the main cause for this impact because of flame retardants and coolants used in the pipelines and compressor stations;

- the photochemical oxidant creation potential of shale gas is higher than all the options except for coal (highest) and biomass, which are 3.4 and 1.6 times higher, respectively;

- fugitive methane emissions from the well and the emission of volatile organic compounds from diesel power drilling equipment are the main contributors to this impact;
- the terrestrial ecotoxicity potential of shale gas is up to 133 times higher than conventional gas, LNG, hydroelectricity, nuclear power and solar;
- coal, wind and biomass (highest) have a terrestrial toxicity up to 2.5 times higher than shale gas; and
- the disposal of drilling waste, like what was found for the other toxicities, is the main contributor for this impact.

1.1.2. Economic impacts

- It would cost £18.63 million to bring a shale gas well into operation and maintain operation over its operating lifespan;
- the equipment used for hydraulic fracturing makes up 51% of the capital cost;
- the life cycle cost of shale gas extracted ranges from 0.13-15.76 p/kWh, averaging at 1.29 p/kWh;
- the break-even price of shale gas ranges from 0.26-31.79 p/kWh, averaging at 2.63 p/kWh;
- the cost of producing shale gas is sensitive to gas price and discount rate;
- the breakeven gas price is higher than US shale gas and UK conventional North Sea gas by 2.4-fold and 25%, respectively;
- the price at which shale gas can be sold at is higher than most market (spot) prices, suggesting that shale gas is not competitive in the gas market;
- the life cycle cost of electricity generated from shale gas ranges from 2.02-132.25 p/kWh, with medium values in the range 8.42-14.04 p/kWh; and
- the life cycle cost of shale gas electricity is up to 43% lower than, coal, hydroelectricity, solar PV and biomass electricity, suggesting it is competitive in the electricity market, but conventional gas, nuclear power and wind electricity have a lower life cycle cost.

1.1.3. Social impacts

- The shale gas electricity life cycle has the lowest employment rate per unit of electricity generated;
- the predevelopment stage and power plant provide the largest number of jobs while the gas production stage produces the smallest;
- the employment opportunities created by shale gas electricity will be restricted as specialised workers, such as hydraulic fracturing engineers, who have experience in shale gas development are needed, which will restrict the number of jobs created going to locals;
- the renewable options have the highest employment rate because of the large workforce needed for maintenance and construction and therefore they would benefit the UK more in terms of employment generation;
- the development of a UK shale gas industry presents an opportunity for the UK oil and gas industry to improve its gender equality;
- the worker injury rate of shale gas is the lowest out of all the options, partially related to the low employment (see next bullet point), but the types of jobs involved in the life cycle have lower accident rates than jobs in sectors such as construction and therefore shale gas can be viewed as a good option for worker safety;
- noise produced as a result of shale gas extraction is comparable to common noises such as traffic and washing machines, ranging between 35-65 dB;
- shale gas development will result in a 3-30% increase in traffic volume and a 3-31% increase in congestion on roads around the well site;
- shale gas has low public support, second to coal, which is the result of a high percentage of surveyed participants being ‘uncertain’ or ‘don’t know’ on their stance, which suggests that shale gas has a poor public image, but also suggests improvements to its public image could help increase support;
- there is a media presence skewed away from shale gas operators, as indicated by their lack of social media impacts, shifting the opinion and information presented in social media about shale gas to those of non-government organisations;
- the capital spending of shale gas presents an opportunity for UK businesses and suppliers (up to £15.12 billion in spending) but the need for specialised hydraulic

fracturing equipment and the number of drilling rigs needed will limit the amount which can be spent on UK businesses;

- the money given to local communities from power plants and shale gas operators is a small percentage (0.73-2.23%) of their revenue, but the money could be beneficial to local authorities and councils, as currently many council budgets are being cut;
- shale gas is a completely indigenous fuel source which could help the UK improve its energy security but the degree to which it does would depend on the volume extracted and how this compares with import volumes;
- the wastewater produced as a result of hydraulic fracturing could put strain on wastewater treatment facilities, because the volume of waste produced is large (871-75,000 m^3) and the composition is beyond the capability of most conventional treatment facilities;
- the need to transport wastewater by tanker truck to the treatment facility could cause an increase in traffic on roads close to treatment facilities, as up to 3,606 trick trips will be needed to transport all the wastewater;
- there is a large overlap in the area covered by the Bowland-Hodder shale play and areas of cultural importance, which could put further restraints and restrictions to the areas available for shale gas exploration because of conflicts of interest;
- the consequential restriction and restrain could lead to an amplification in impacts from noise, traffic and wastewater as drilling could be concentrated to specific areas; and
- more regulatory staff are needed in the UK, if the country is to develop a shale gas industry, as well's require a minimum of 40 inspections over its lifespan.

1.1.4. Overall sustainability of shale gas electricity

- When equal importance is allocated to all aspects and indicators, shale gas ranks seventh out of nine while wind and solar PV rank top and coal ranks bottom;
- when the importance is shifted, hydroelectricity becomes the top option when the environmental aspect is more important than the other two, but when it is less important, solar PV becomes the best option;
- when the economic aspect is more important, solar PV become the best options, but when it is less important, hydroelectricity is the best option;

- when the social aspect is more important, solar PV is the best option, but when it is less important, LNG is the best option; and
- in order to make shale gas the best option, significant improvements to its performance are needed in combination with large shifts in aspect and indicator weighting, which suggests that shale gas is not a sustainable electricity option for the UK.

1.2. Sustainability assessment of shale gas in the electricity mix

1.2.1. Environmental impacts

- The environmental impacts in the 2030 gas mixes increase in comparison to the 2012 mix, by between 28% and 2.5 fold, because of the decrease in the percentage of domestically produced gas in the future mixes;
- an increased penetration of shale gas in the mix increases environmental impacts for eight out of the 11 impact categories: elemental abiotic resource depletion, eutrophication, ozone depletion, photochemical oxidant creation and toxicity (freshwater, human, marine and terrestrial), which are the impacts for which shale gas has higher impacts than conventional gas and LNG;
- in the higher penetration mix, the global warming potential decreases as a result of shale gas displacing LNG in the gas mix;
- the impact of shale gas on the electricity mix is small, but the mix with the higher penetration has higher environmental impacts for nine of the 11 impact categories by up to 15%; and
- both future mixes have lower environmental impacts than the 2012 mix, which is because of the decrease in coal generation and the increase in renewables.

1.2.2. Economic impacts

- Shale gas will not reduce gas costs because it is more expensive than gas imports;
- gas prices are 7% higher in the high penetration scenario than in the low penetration scenario;
- shale gas will have a negligible effect on electricity costs, but the mix with the higher penetration has the higher electricity cost; and

- the reduction in the contribution of gas electricity in the future mixes means that the impact of shale gas on energy prices is limited.

1.2.3. Social impacts

- Energy security in the 2030 gas and electricity mixes is comparable to that of the 2012 mix, as the diversity of fuel supply (DFS) score is similar;
- the low shale penetration gas mix has a lower DFS than the high penetration mix (0.92 vs 0.82) but both are lower than the DFS of the 2012 mix (0.94). This is because the number of import countries decreases in the future and total the volume of shale gas does not compensate enough for the decline in North Sea gas production ;
- the high shale penetration electricity scenario has a higher DFS (0.93) than both the low scenario (0.90) and 2012 electricity mix (0.90); and
- the degree to which energy security increases depends on the scale of production and penetration of shale gas into the energy market; higher shale gas production higher energy security.

1.2.4. Overall sustainability of shale gas in the electricity mix

- shale gas is not a favourable option for the UK;
- the mix with less shale gas scores better in the MCDA when equal importance is given to all aspects and indicators;
- when less importance is given to the environmental aspect, the high shale gas penetration scenario scores better; and
- both the 2030 electricity mixes score better than the 2012 mix because of the large drop in coal generation and the growth of renewables in the 2030 mixes.

2. Recommendations

From the results and findings of this work (chapters 2 to 6) the following recommendations, for industry and policy makers, can be made on how to improve shale gas development in the UK to make it more sustainable. Recommendations to target specific aspects/impacts (in order of appearance in chapters 2 to 6) are listed first, followed by general recommendations not specific to any aspect/impact:

- shale gas has lower environmental impacts than coal but has (in general) higher impacts than renewables and, therefore, in an electric mix, shale gas should be used to replace coal if the environmental sustainability of UK electricity is to improve;

- to reduce CO_2 emissions from the electricity mix, shale gas can be used to replace LNG as it has a lower global warming potential;
- the main contributors to environmental impacts are the disposal of drilling waste and combustion of gas in the power plant; thus, these two life cycle stages should be targeted to reduce the environmental impacts of shale gas;
- impacts from drilling waste disposal can be reduced by reducing the amount of drilling fluid used, as well as reducing the amount of waste disposed of by land-spreading and using drilling fluids that contain less toxic chemicals;
- to reduce impacts from the power plant, the efficiency of the power plant needs to be improved, which can be achieved by gas turbine design improvements and heat recovery in the form of combined heat and power to maximise the use of the energy produced from gas combustion; any improvements to the power plant are also applicable to the other gas options (conventional gas and LNG);
- best available technology and practice should be used to reduce emissions and impacts from other life cycle stages in the life cycle of shale gas electricity, such as green completion and checking the integrity of pipelines and equipment;
- legislation and regulations specific to shale gas should be developed, enforcing the use of best practice and best available technology. Life cycle considerations should also be enshrined in legislation, which along with regulation should be reviewed regularly to assess their effectiveness and relevance;
- baseline data should be collected on seismic activity, air, water and soil quality, as well as biodiversity, followed by long-term monitoring during and after production, to enable accurate assessments of the environmental impact of shale gas development in an area;
- to reduce the cost of producing shale gas and to reduce the dependence on US technology and knowledge, it is important to invest in domestic research and development and increase collaborations between industry, Government and academia;
- the jobs in the shale gas industry are well paid, so it is important that as many jobs as possible go to UK residents to maximise the economic contribution to the UK

economy; this can be achieved by training and schooling in specialised centres to develop a domestic skill base;

- the activities which produce the most noise should be carried out during hours which are least disruptive to local residents, such as middle of the day during the working week; this includes the use of equipment and transport to and from well sites;

- effective planning and management of development need to be implemented in order to minimise disruptions to the everyday lives of people living close to well sites. This can be achieved by two-way communication with local residents, agreeing in advance the timetable or schedule of activities (drilling, hydraulic fracturing, equipment deliveries and pickups etc.);

- health and safety standards and guidelines for residents living near well sites should be formulated and made publically available;

- planning and management is also important for associated activities, in particular wastewater treatment, to ensure shale gas does not cause strain to existing municipal facilities; this can be achieved, for example, through contingencies for onsite wastewater storage to enable timely deliveries of wastewater to treatment plants;

- more effective and open communication by shale gas operators is needed to improve their conventional and social media presence, to balance the coverage on shale gas in the media and engage better with the public;

- shale gas has low public support, which can also be addressed by increased and effective communication strategies. Examples of such strategies include question and answer sessions between the operators and public, workshops and drop in sessions, as well as interactive visitor centres, which can help increase the understanding of what shale gas is and how it is extracted, as well as build trust between the operator and local residents;

- shale gas could help the UK reduce its dependence on energy imports and therefore this needs to be depicted in the 'big picture', such as national energy policies and frameworks so its relevance in the energy mix can be seen;

- decisions on the development of shale gas need to consider the inputs of all relevant stakeholders and take into account environmental, economic and social aspects on a life cycle basis;

- regulating the industry effectively will require adequate staff numbers and should be provided by independent and neutral bodies, such as Government departments; regulations need to be enforced and inspections carried out regularly to reduce incidents of license and permit breaches;

- a long-term strategy for reducing the environmental and social impacts of shale gas should be developed and reviewed regularly during its exploitation to ensure it remains relevant;

- Government support for shale gas is primarily driven by the expectation that it will improve energy security and benefit the economy. However they do not consider a wider range of impacts that includes all aspects of sustainability. Therefore, the Government should consider a larger number of impacts that cover all aspects of sustainability in their decision making;

- Government decision making should also consider the whole life cycle and supply chain, rather than focusing on a single activity or life cycle stage, to avoid shifting the impacts from one stage to another;

- if new regulation is to be introduced, the Government should adopt a life cycle approach to identify hot spots and potential areas of concern, such as wastewater management and drilling waste disposal;

- shale gas should be included in future Government energy and emission models, as well as long-term energy and climate change goals. These should be used in future decision making on the structure of the UK electricity market and mix and should include multiple scenarios over different time frames and scenarios with and without shale gas;

- in addition to the wealth fund and community charter, the Government should consider an environmental legacy fund, in which funds collected would go towards compensating environmental damages caused by shale gas development as well as contribute towards ensuring proper well site decommissioning and land remediation;

- a fund should also be setup to cover the cost of decommissioning abandoned and orphaned wells, so that the burden is not borne by the tax payer. The fund should cover the full cost of plugging and other decommissioning activities, as well as well integrity monitoring in later years; and

- if the Government were to prolong the economic benefits of shale gas, adopting a sovereignty fund similar to that of Norway and Qatar could be beneficial, as the tax revenue collected is invested into outside assets and projects which would prolong the longevity of shale gas tax revenue.

3. Future work recommendations

Based on the results and literature synthesis of this work, the following future work (presented in order of aspect/impact appearance in chapters 2 to 6) is needed:

- better understanding of effect of shale gas development on human health, especially involving professional medical diagnosis;
- long-term monitoring and quantification of health impacts in collaboration with medical professionals rather than relying on self-reporting surveys;
- further studies on the human and eco-toxicity of fracturing and drilling fluids, as well as the long-term health impacts and eco-toxicity of shale gas exploitation;
- understanding of the mechanisms behind the delayed production of hydrogen sulphide in shale gas extraction;
- understanding subsurface chemical reactions of hydraulic fracturing chemicals and how they could affect wastewater treatment;
- evaluating the impact of land use change, both direct and indirect, on greenhouse gas emissions and climate change;
- development of technologies appropriate and capable of treating wastewater produced as a result of hydraulic fracturing;
- better understanding of the environmental impacts of shale gas development beyond those considered in this work, such as biodiversity, land transformation and emissions of particulate matter;
- grouping environmental indicators (end-point indicators) in MCDA or using end-point LCIA method;
- effects of various tax incentives for shale gas on low-carbon fuels, such as nuclear and renewables and vice versa;
- assessment of the economic viability of shale gas a fuel for heat generation or as a feedstock in the chemicals industry;
- evaluation of social impacts beyond those considered in this work, such as equality and diversity (other than gender), impact of development on house prices,

geopolitics, long-term health impacts, insurance and impact of community investment;

- studying the lessons learned from other countries (US, Canada and China), in terms of their shale gas impact and community benefit strategies;
- further assessments of the impacts of shale gas to the UK energy mix, considering more scenarios beyond the year 2030; and
- stakeholder engagement studies and surveys to elicit their preference for different sustainability criteria.

4. Concluding remarks

This research has assessed the environmental, economic and social sustainability of shale gas production and electricity generation and integrated them to evaluate its overall sustainability. This research has also analysed the impact on the UK electric mix of incorporating shale gas as part of the mix. The results suggest that, under the conditions considered in this work, shale gas is not a sustainable option for the UK and renewables and nuclear power are better options. However, sustainability trade-offs are needed for all the options, as neither is superior for all or most sustainability aspects.

The results and findings of this research can be used by industry and policy makers as well as NGOs and the general public. Despite it being UK focused, the outcomes, are also transferable to other countries considering developing shale gas.

Appendices

Appendix A

AI. Shale gas formation and extraction

AII. Life cycles of alternative electricity options

AIII. The life cycle assessment (LCA) methodology

AIV. Approach taken in this LCA

AV. Life cycle inventory data

AVI. Economic sustainability assessment

AVII. Social sustainability assessment

AVIII. Multi-criteria decision analysis

Appendix B

BI. Data for different well sizes

BII. Drilling fluid and waste

BIII. Shale gas composition

BIV. Estimated ultimate recovery

BV. Data used for LCA modelling

BVI. Land use change

Appendix C

CI. Capital cost of a shale gas well

CII. Sand and chemical quantities

CIII. Break-even price at different discount rates

CIV. Electricity costs

Appendix D

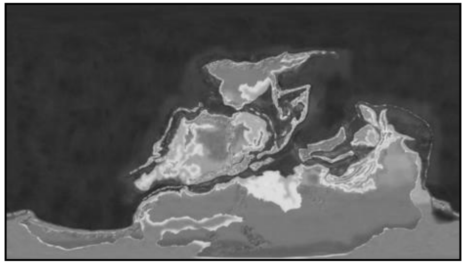
DI. Electricity technologies

Appendix E

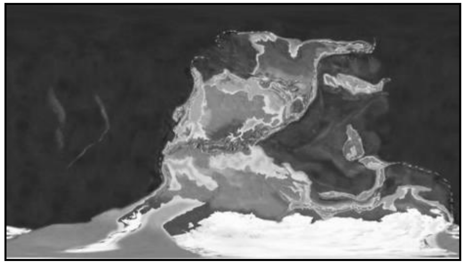
Appendix A

AI. Shale gas formation and extraction

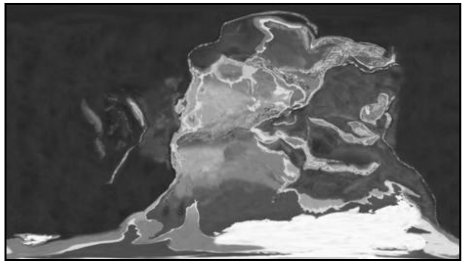
<u>AI.I. Land masses</u>



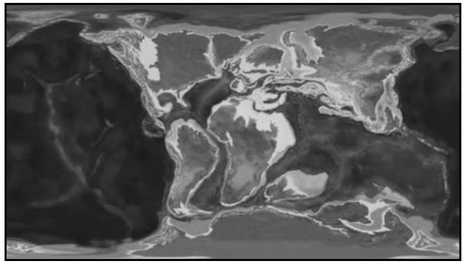
Devonian period: 417 million to 354 million years ago



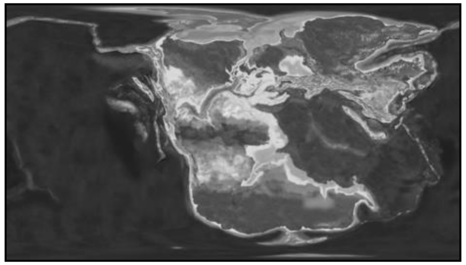
Carboniferous period: 354 million to 290 million years ago



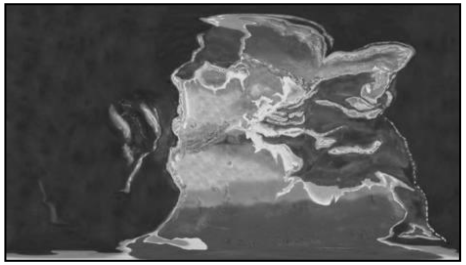
Permian period: 290 million to 248 million years ago



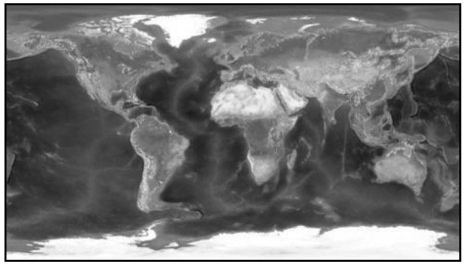
Cretaceous period: 142 million to 65 million years ago



Jurassic period: 205 million to 142 million years ago



Triassic period: 248 million to 205 million years ago



Holocene period (present day)

Figure A1: Diagram of changes to land masses: Devonian period to present day. Darker shades represent water and lighter shades land masses (BBC Nature, 2016).

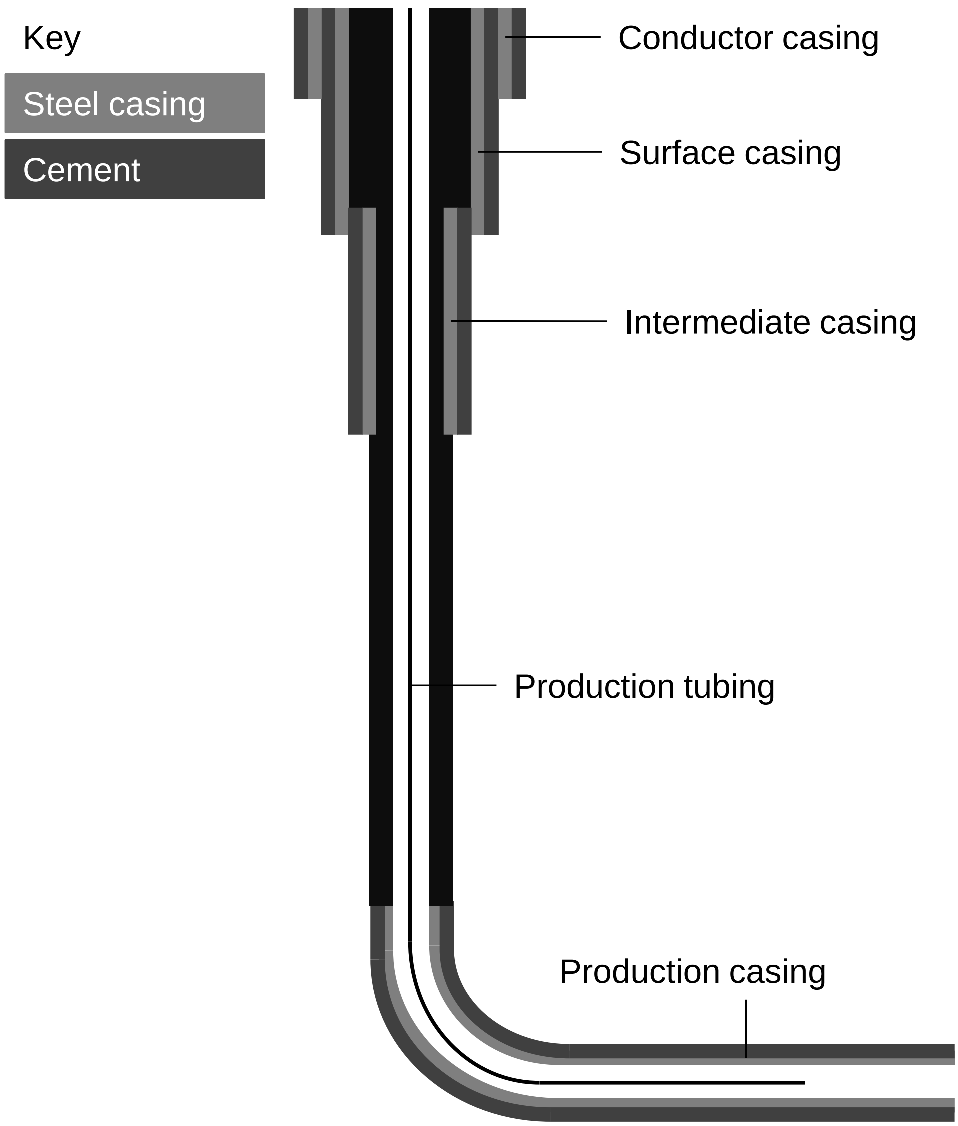


Figure A2: Shale gas well casing and cement diagram.

AI.II. Shale gas life cycle

There are nine stages in the shale gas life cycle. Stages one through to seven concerns setting up a well for gas production while stages eight and nine concern end of life activities. The activities needed to bring a single horizontal well into production are described. Shale gas well pads typically consists of multiple wells- four to eight horizontal wells stemming from a single vertical well. In the case of multiple well, stages two to six are repeated. Also, a horizontal well may be re-fractured to increase its productivity, in which case, stages five and six are repeated.

Stage 1: Road and well pad construction

The land on which the well will be drilled into is called the well pad and the site needs to be prepared for drilling, hydraulic fracturing and gas production. The land needs to be flattened and cleared of vegetation. Roads and other infrastructure are installed if there are none already at the site. Drilling equipment is then brought onsite ready for the next stage. Other equipment is brought onsite as and when required.

Stage 2: Well drilling

The wellbore is drilled. A vertical well is drilled first before directional drilling is used to drill a horizontal well stemming from the vertical one.

Stage 3: Well casing installation

When sections of the well have been drilled, casing is installed to isolate the rock and soil from the well. Cement is pumped in to fill the void (annulus) between the casing and the surrounding rock and soil. The integrity of the casing is testing using acoustic logging and pressure testing. If the casing fails integrity tests, the casing is reinserted and re-cemented.

Stage 4: Horizontal well perforation

The casing in the lateral section of the well is pierced to allow fracturing fluid to come into contact with the rock to be fractured and to allow gas into the well. The well perforating is carried out using explosive charges and is done a section at a time.

Stage 5: Hydraulic fracturing

Fracturing fluid is injected into the well at high pressure, typically around 700 bar (Kissinger et al., 2013; Stephenson et al., 2011), in order to fracture the rock to release gas. The lateral well is hydraulically fractured at sections, starting from the toe end, working towards the heel. Lengths of 100 m are hydraulically fractured at a time.(Clark et al., 2011)

Stage 6: Well completion

The well is depressurised and fracturing fluid flows back up the well (10-300%) of fracturing fluid) (Clark et al., 2013). The fluid that returns to the surface, termed flowback water, is a mixture of fracturing fluid and saline formation water. This is stored in onsite containers to be reused in further hydraulic fracturing or to be taken to wastewater treatment works for treatment. In the US, the most common wastewater management is to dispose of the flowback water in wastewater injection wells.

Stage 7: Gas production

The production tube is inserted into the well, which is connected to the gas processing pipeline onsite. The well produces gas which is processed to remove impurities such as natural gas liquids, CO_2 and H_2S. Shale gas wells have a production lifespan of around 30 years (Clark et al., 2013).

Stage 8: Well abandonment

At the end of the well's production lifespan, the well needs to be plugged with cement and the site cleared of equipment. Monitoring equipment is installed to ensure the integrity of the well is not breach after decommissioning.

Stage 9: Land reclamation

After the well has been decommissioned, the land needed to be restored to its original stage. This may involve re-vegetation and land re-contouring.

AII. Life cycles of alternative electricity options

The life cycles of the other electricity options considered in this work are shown in Figures A3 to A9.

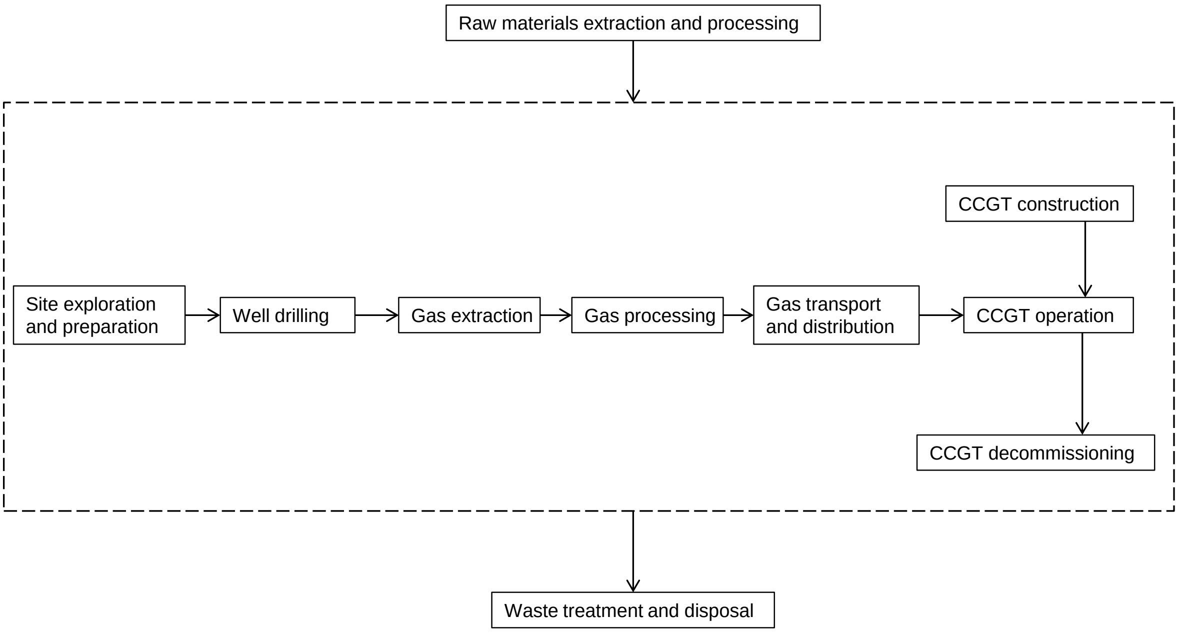


Figure A3: Life cycle system boundary of conventional gas electricity. CCGT- combined cycle gas turbine.

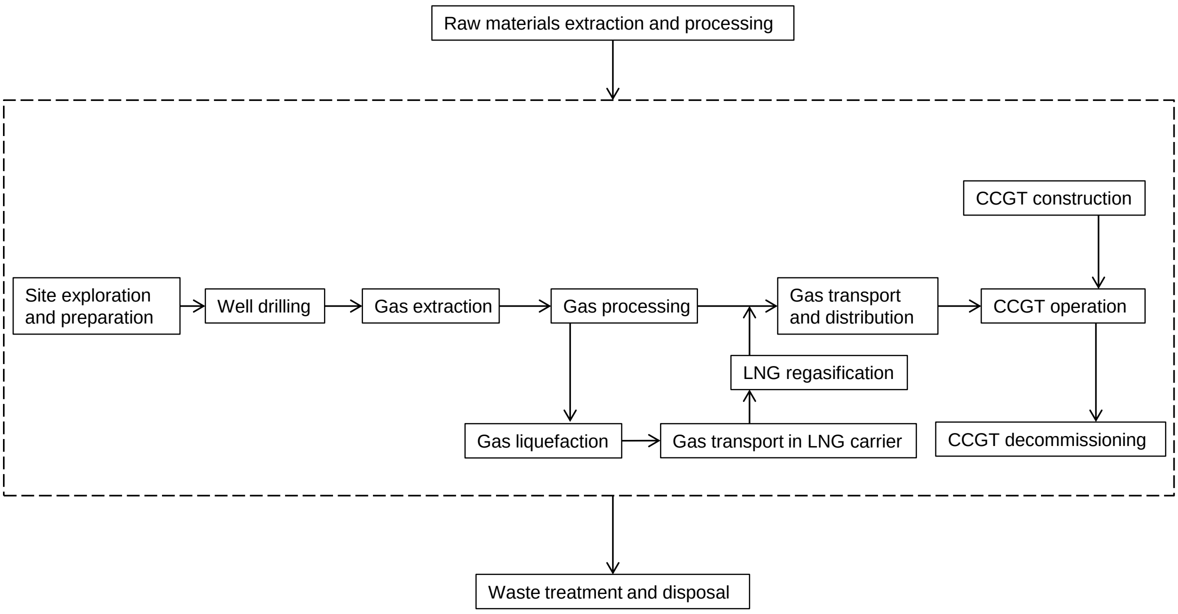


Figure A4: Life cycle system boundary of liquefied natural gas (LNG) electricity. CCGT- combined cycle gas turbine.

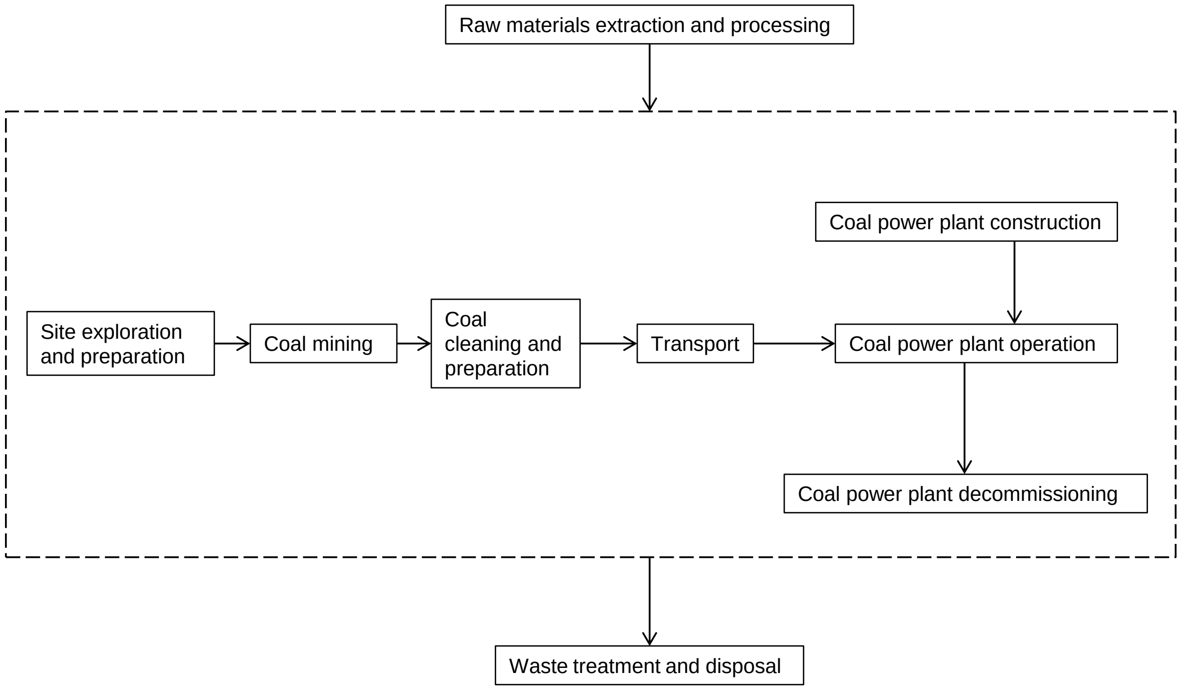


Figure A5: Life cycle system boundary of coal electricity.

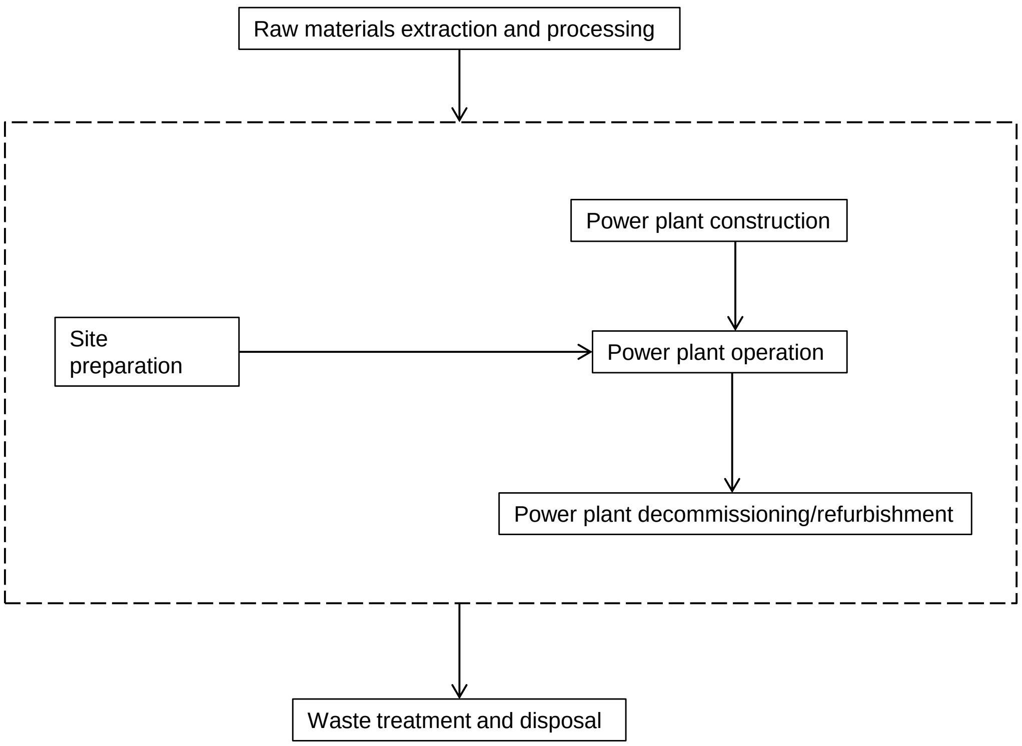


Figure A6: Life cycle system boundary of hydroelectricity.

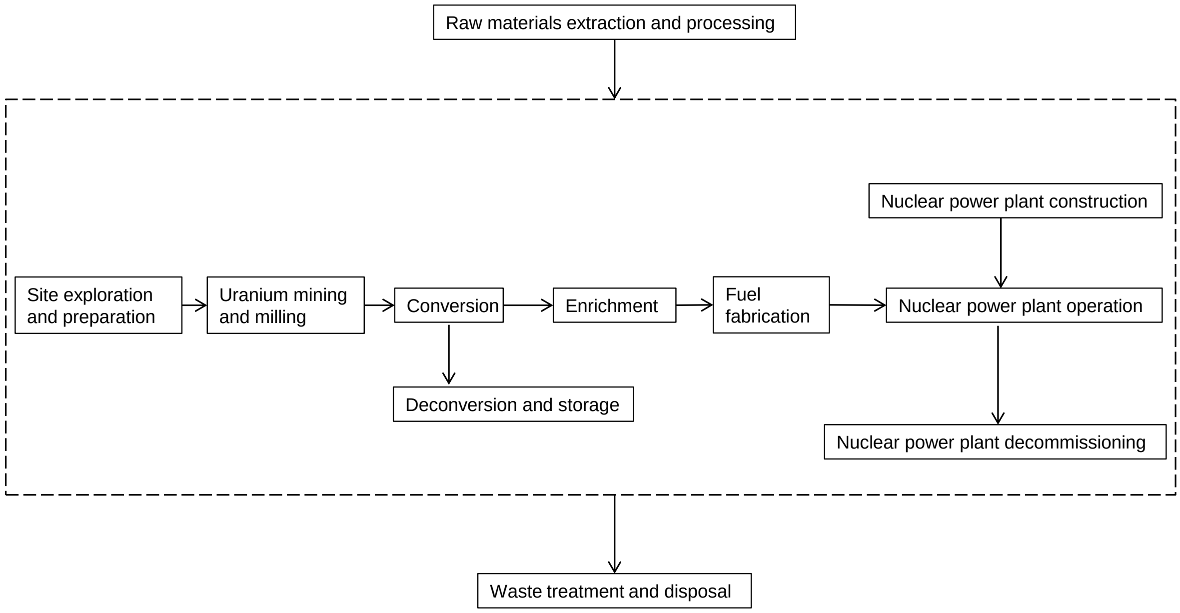


Figure A7: Life cycle system boundary of nuclear power.

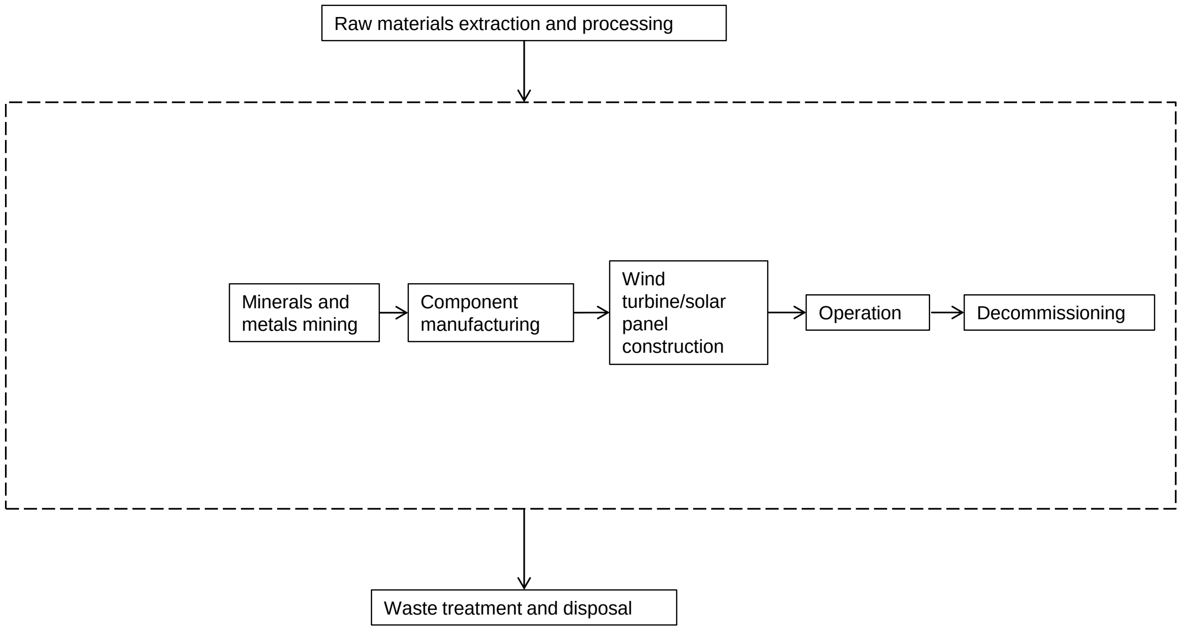


Figure A8: Life cycle system boundary of wind and solar photovoltaic (PV) electricity.

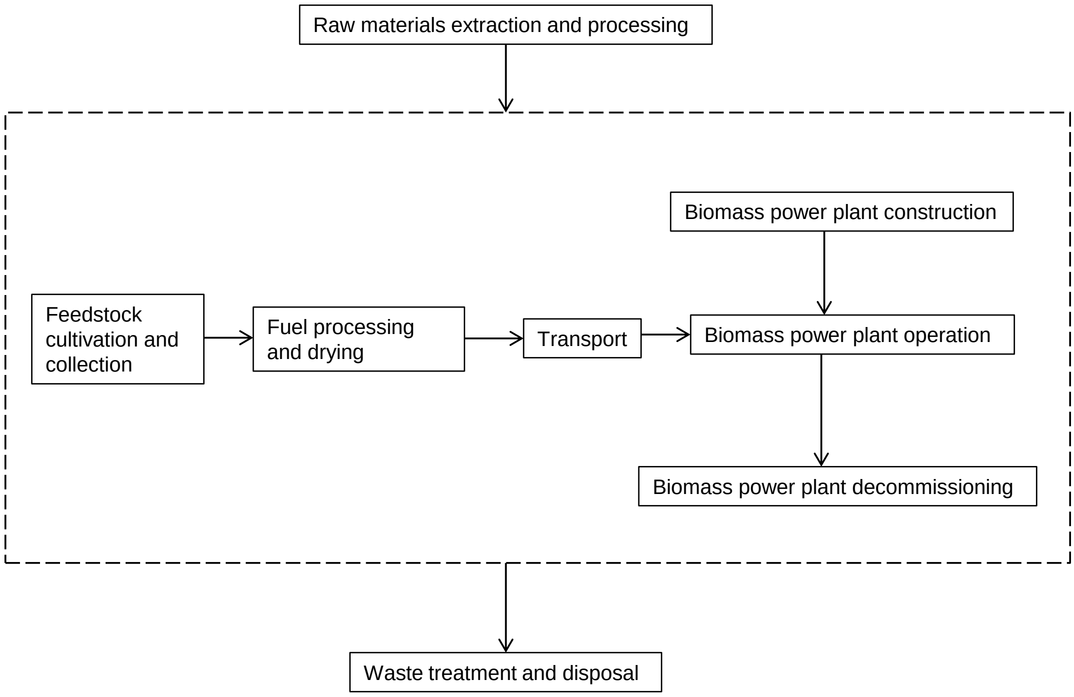


Figure A9: Life cycle system boundary of biomass electricity.

AIII. The life cycle assessment (LCA) methodology

Life cycle assessment (LCA) is a tool used for environmental system analysis, translating life cycle thinking into measurable quantities (Azapagic et al., 2011; Baumann and Tillman, 2004). Environmental impact assessment and cost-benefit analysis are other tools which can be used for environmental analysis but focus on specific metrics, while LCA is comprehensive, incorporating social, technical and natural systems and their relationships (Baumann and Tillman, 2004). In addition to this, LCA is a mature and well established method which has been used in industry and academia for task such as: 'hot spot' identification, measuring environmental sustainability and comparing options to identify which is more sustainable (Azapagic et al., 2011; Baumann and Tillman, 2004). LCA assesses environmental sustainability by using indicators to measure the impact of products/services to the environment, including and not limited to: toxicity, greenhouse gas emissions and ozone depletion (Azapagic et al., 2011; Baumann and Tillman, 2004). The lower the impact is the better and therefore when selecting the most environmentally sustainable option, the one with the lowest impact is the one considered the most 'sustainable'.

The LCA methodology is standardised by the International Organization for Standardization (ISO) in ISO 14040 (ISO, 2006a; ISO, 2006b). In ISO 14040, LCA is defined as "a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product throughout its life cycle" (ISO, 2006a). ISO 14040 also sets out the stages to be carried out when conducting an LCA study. The methodology consists of four stages, each containing their own steps (compulsory and optional) that are to be taken. The methodology is iterative, as indicated by the arrows in Figure A10, so stages can be revisited as and when more or better data becomes available:

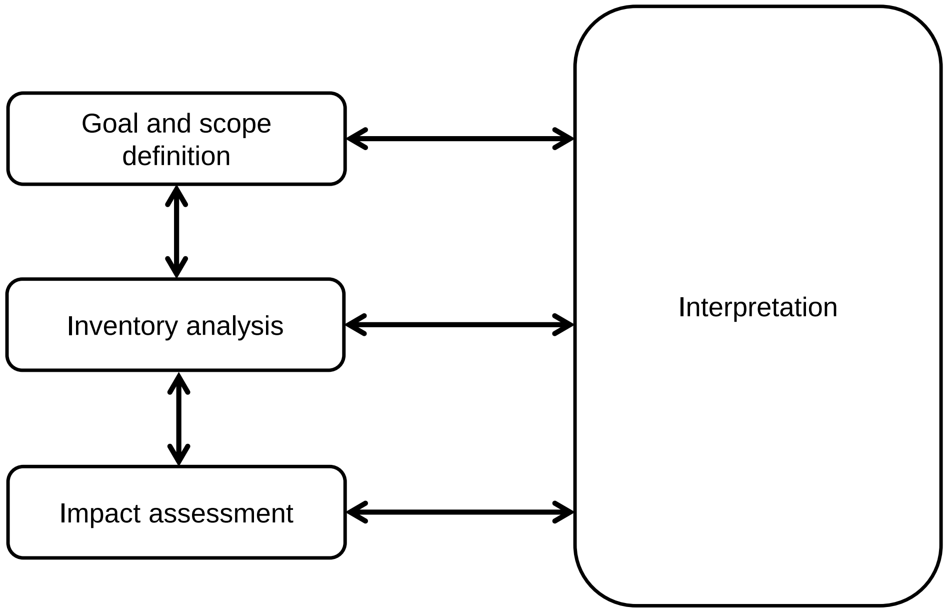


Figure A10: Diagram of LCA stages. The methodology is iterative, as indicated by the double headed arrows. This means that stages can be revisited and recalculated/re-evaluated as and when more accurate data becomes available (ISO, 2006a).

1. Goal and scope definition

In the first LCA stage, the purpose statement and intended use of the study need to be defined (ISO, 2006a). Other steps in this stage are to set and state the system boundaries, functional unit, data quality and assumptions (ISO, 2006a). The system boundary specifies which stages in the life cycle are considered, as well as how in depth into the life cycle the study delves. The functional unit represents how and what the output of the system is being delivered and measured (e.g. per kWh electricity generated, per m^2 area covered). If the study is comparing equivalent alternatives, it is important that the same functional unit is used to make the comparison fair. The data quality and assumptions can be evaluated at the end of the LCA (ISO, 2006a). The data quality is graded on its appropriateness and representativeness of the system modelled, while assumptions can be assessed in a sensitivity analysis to see the impact changes to assumptions have on the results.

2. Life cycle inventory or inventory analysis

The second and often the most time consuming stage of LCA (Baumann and Tillman, 2004), is the stage in which environmental burdens (material, energy and emission flows in the system) are identified and quantified. This is done by constructing a model of the system, based on the defined system boundary (Azapagic et al., 2011). The burdens (B_j) are quantified based on the activities in the system boundary and are calculated from (Azapagic et al., 2011):

$$B_j=\sum_{i=1}^{I} b_{j,i}\times z_i \quad \text{(A1)}$$

where:

$b_{j,I}$ burden j for activity i

z_i mass or energy flow of activity i

i activity

j burden category e.g. emission of CO_2.

If the system has multiple products, allocation is used, for which ISO 14044 sets out three options (ISO, 2006b):

i. system expansion or subdivision to avoid allocation;

ii. mass based; and

iii. economic based.

The allocation method used will affect the results of the LCA.

3. Life cycle impact assessment (LCIA)

This is the step in which the environmental burdens are quantified into potential environmental impacts or category indicators. This is done by following a three step procedure (ISO, 2006a):

i. selection of impact categories, category indicators and LCIA model;

ii. classification; and

iii. characterisation.

With three optional additional steps (ISO, 2006a):

- normalisation;

- grouping; and
- weighting.

The aim of this step is to narrow the burdens (B_j) by aggregating them into impact categories (classification) reflective of their potential impacts on both human and ecological health, which results in multiple impacts being associated with one burden (Azapagic et al., 2011). For example, methane contributes towards global warming and photo-oxidant formation. The characterisation result depends on the LCIA method selected, which is discussed further in this section.

The environmental impacts are calculated by converting B_j into impacts (E_k) (Azapagic et al., 2011):

$$E_k=\sum_{j=1}^{J} e_{k,j}\times B_j \tag{A2}$$

where:

$e_{k,j}$ characterisation factor, representative of contribution of burden B_j towards impact E_k

k impact category e.g. global warming, ozone depletion, water toxicity etc.

In principle, LCIA methods and models are either: mid-point (also known as problem-orientated) or end-point (also known as damage-orientated) (Azapagic et al., 2011; Guinée et al., 2002). In the mid-point approach, environmental burdens are aggregated according to their relative contribution to environmental impacts they might cause (Guinée et al., 2002). They link environmental burdens to an intermediate point between occurrence/intervention and ultimate damage, hence the name mid-point. The impacts calculated refer to potential rather than actual impacts and damage, as they are quantified at an intermediate point, as indicated in Figure A11. This approach is currently considered ‘best available practice’ for LCIA, as the indicators are defined mid-way in the environmental mechanism, in congregation with current environmental policy themes (Azapagic et al., 2011). This also allows models to be relatively accurate and flexible in the choice of characterisation model and the position of indicators. The CML 2001 (Centrum Milieukunde Leiden, Environmental Centre Leiden) method is one of the most mature methods and the most widely used mid-point method (Azapagic et al., 2011). Therefore it was used to evaluate the environmental sustainability of UK shale gas used for electricity generation. Other methods are TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) and ReCiPE (RIVM and Radboud University, CML and PRé) which are newer methods.

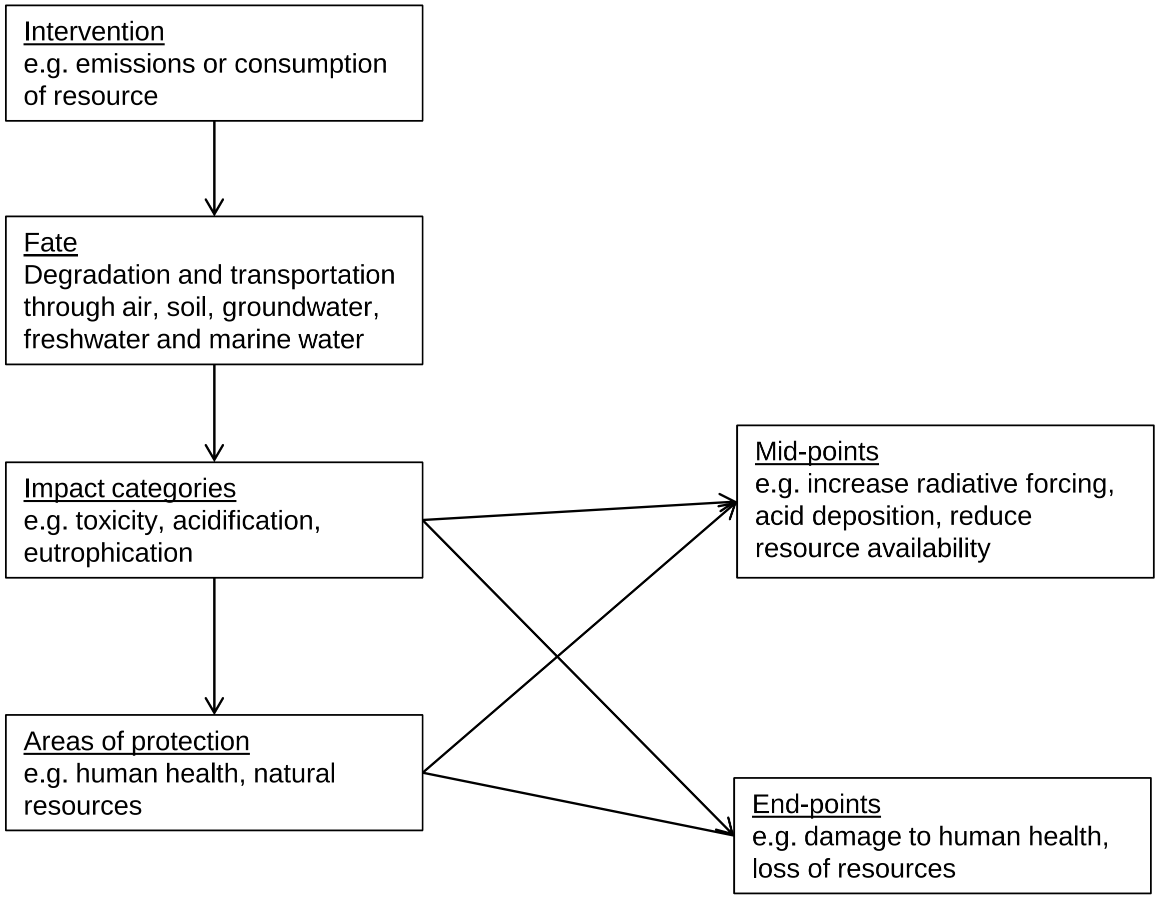


Figure A11: Diagram of LCIA methods. Mid-point approaches calculate potential harm to the environment while end-point estimate damage to areas of protection (Goedkoop et al., 2013).

In the end-point approach, the damage caused by burdens is modelled, as shown in Figure A11. The impacts calculated are the damage to the areas of protection (human health and the natural and man-made environment), giving them greater relevance environmentally but are less accurate to model and less comprehensive than mid-point indicators (Azapagic et al., 2011; Guinée et al., 2002). The approach is still being developed, which is why the mid-point approach is considered best practice. The most widely used end-point method is Eco-indicator 99 (Azapagic et al., 2011).

4. Interpretation

In the final stage of the LCA methodology, the major burdens (impacts and 'hot spots') are identified, in addition to a sensitivity analysis to evaluate the reliability and accuracy of the results (ISO, 2006a). From the results, recommendations can be made as to how a system, product or process can be improved. The results also need to be reported transparently and free of bias.

This gives a general overview of what ISO 14040 and 14044 set out for the LCA methodology, but despite setting out an international reference for how to conduct an LCA study, there is no outline for how the environmental burdens should be converted into impacts. As a result, there are a number of LCIA methods and models which have been developed, which has led to there being numerous indicators and impacts used to measure environmental sustainability (Azapagic et al., 2011; Baumann and Tillman, 2004).

AIV. Approach taken in this LCA

To conduct the LCA, software is used. There are many software packages available, most of which incorporate LCIA methodologies. This makes them useful tools for conducting LCA studies. Also, as large amounts of data are often collected in the LCI stage (Baumann and Tillman, 2004), software can provide great assistance in data storage and organisation. To conduct the LCA study, GaBi v.6 software was used. GaBi is a leading tool used for life cycle engineering, modelling and balances (PE, 2012; thinkstep, 1992-2016). The software allows systems to be modelled in a modular system, made up of plans, processes and flows, giving it a clear and transparent structure (PE, 2012; thinkstep, 1992-2016). The software and databases are independent from one another, with all information related to a process stored in databases predefined according to a basic structure (PE, 2012; thinkstep, 1992-2016).

The software supplies the user interface and the ability to construct and analyse databases. The user may create or change databases and reinsert them into a model. The Ecoinvent V2.2 database can be integrated into GaBi and was one of the main sources of data used in this work. Ecoinvent is a publically available LCI database covering many sectors, including energy (fossil fuel and renewables), transport and chemicals (Ecoinvent Centre, 2010). The databases are consistent, transparent and independent which is why they were used. Another source of data used in this work is GEMIS, a software package that can be used to calculate life cycle balances as well as material flows. GEMIS was used to calculate the emission factors of shale gas combustion i.e. flue gas composition (IINAS, 2017). To calculate the environmental impacts of shale gas electricity, the CML LCIA method was used within GaBi.

The CML method is a ready-made LCIA methodology, so the LCA practitioner does not need to go in-depth into the procedures of different impact assessment steps (Guinée et al., 2002; Heijungs et al., 1992). In this method, environmental burdens are aggregated according to their relative contribution to the environmental problem or impact they may potentially cause. Eleven (mid-point) environmental impact categories are calculated (Guinée et al., 2002; Heijungs et al., 1992) in this method covering impacts to air, water and land, which were used to assess the environmental sustainability of UK shale gas electricity. The impact categories are listed below (Azapagic et al., 2011; Guinée et al., 2002; Heijungs et al., 1992).

AIV.I. CML indicators

Abiotic resource depletion

The depletion of abiotic resources (i.e. fossil fuels, metal and minerals) measures either elemental abiotic resource depletion (ADP_e) or fossil fuel abiotic resource depletion (ADP_f) (Azapagic et al., 2011; Guinée et al., 2002; Heijungs et al., 1992; van Oers et al., 2002). Fossil fuel depletion is measure in MJ while elemental (i.e. metal and minerals) depletion is measured in kg antinomy (Sb) equivalent (van Oers et al., 2002). Antinomy is used as the benchmark as it is one of the most important elements used in the world (gold, antimony, lead, silver, copper and sulphur). It was first used as a benchmark by Guinee and Heijung, because out of the important elements it is the first alphabetically (Guinee and Heijungs, 2013). Their benchmark has been used since and the benchmark can be switched to another element by scaling. For example, to convert from Sb to Au (gold), multiply the ADP_e by 5.2 (Au has an ADP_e 5.2 times larger than Sb) (Guinee, 1995). A similar approach can be applied to the other CML indicators. From equation A1, the ADP (and other impact categories) is calculated from (Azapagic et al., 2011):

$$ADP_e = \sum_{j=1}^{J} ADP_{e,j} \times B_j \qquad \text{(kg Sb}_{\text{-Eq.}}\text{)} \qquad \text{(A3)}$$

where:

ADP_e elemental resource depletion potential (kg $Sb_{-Eq.}$)

j elemental resource j (-)

J total number of elemental resources (-)

$ADP_{e,j}$ elemental resource depletion potential of resource j (kg $Sb_{-Eq.}$/kg resource)

B_j amount of elemental resource j consumed/depleted (kg resource).

$$ADP_f = \sum_{j=1}^{J} ADP_{f,j} \times B_j \qquad \text{(MJ)} \qquad \text{(A4)}$$

where:

ADP_f fossil fuel resource depletion potential (MJ)

j fossil fuel resource j (-)

J total number of fossil fuel resources (-)

$ADP_{f,j}$ fossil fuel resource depletion potential of resource j (MJ/kg resource)

B_j amount of fossil fuel resource j consumed/depleted (kg resource).

Acidification potential (AP)

The potential for acid deposition from sulphur dioxide (SO_2), nitrous oxides (NO_x) and ammonia (NH_3) into water bodies and soil, causing the pH to become more acidic is measured by the AP (Azapagic et al., 2011; Heijungs et al., 1992). This would cause harm to wildlife and vegetation as fish are sensitive to pH (eggs will not hatch at pH<5) and an increase in soil acidity can kill microbes in the soil, resulting in nutrient leaching because of the change in soil chemistry (EPA, 2016a). The AP is measured in kg SO_2 equivalent. SO_2 is used as the benchmark because it is one of the major acidifying pollutants and, out of SO_2, NO_x and NH_3, forms the strongest acid (Hall et al., 2006; Thermidaire, 2014). The AP is calculated from (Azapagic et al., 2011):

$$AP = \sum_{j=1}^{J} GWP_j \times B_j \qquad (\text{kg } SO_{2\text{-Eq.}}) \qquad \text{(A5)}$$

where:

AP: acidification depletion potential (kg $SO_{2\text{-Eq.}}$)

j acid gas j (-)

J total number of acid gases (-)

AP_j acidification potential of gas j (kg $SO_{2\text{-Eq.}}$/kg gas)

B_j amount of acid gas j emitted (kg gas).

Eutrophication potential (EP)

The EP measures the potential for nutrients to cause over-fertilisation in water and soil, causing phenomena such as algal bloom (Heijungs et al., 1992). The EP is measured in kg phosphate (PO_4^{3-}) equivalent. PO_4^{3-} is used as the benchmark as phosphor is limiting in freshwater eutrophication, the most common form of eutrophication (Guinée et al., 2002; Guinée et al., 1996; Smith et al., 1999). The EP is calculated from (Azapagic et al., 2011):

$$EP = \sum_{j=1}^{J} EP_j \times B_j \qquad (\text{kg } PO_4^{3-}{}_{\text{Eq.}}) \qquad \text{(A6)}$$

where:

EP eutrophication depletion potential (kg $PO_4^{3-}{}_{\text{Eq.}}$)

j nutrient j (-)

J total number of nutrients (-)

EP_j eutrophication depletion potential of nutrient j (kg $PO_4^{3-}{}_{Eq.}$/kg nutrient)

B_j amount of nutrient j emitted (kg nutrient).

Climate change/global warming potential (GWP)

The potential for climate change is measured by the GWP, which is a measure of the amount of heat trapped by atmospheric greenhouse gases (GHG) (Heijungs et al., 1992). The total GWP of the different GHG is measured in kg CO_2 equivalent. CO_2 is used as the benchmark as it is the most prolific GHG, at roughly 72% of total atmospheric GHG (Blasing, 2016). The GWP is calculated from (Azapagic et al., 2011):

$$GWP=\sum_{j=1}^{J} GWP_j \times B_j \qquad (\text{kg } CO_{2\text{-Eq.}}) \qquad \text{(A7)}$$

where:

GWP global warming potential (kg $CO_{2\text{-Eq.}}$)

j greenhouse gas j (-)

J total number of greenhouse gases (-)

GWP_j global warming potential of greenhouse gas j (kg $CO_{2\text{-Eq.}}$/kg greenhouse gas)

B_j amount of greenhouse gas j emitted (kg greenhouse gas).

Ozone depletion potential (ODP)

The ODP is a measure of the potential for emissions of ozone depleting substances (ODS) to deplete the ozone layer, measured in kg tricholorofluoromethane (CFC-11) equivalent (Heijungs et al., 1992). The Earth's ozone layer absorbs 97% to 99% of ultraviolet B radiation emitted from the Sun, which would cause harm and damage to life forms if it were to reach the Earth's surface (EPA, 2016b). CFC-11 is one of two major ODS, the other being methyl chloroform, and has the longer residence time (WMO, 2012). The ODP is calculated from (Azapagic et al., 2011):

$$ODP=\sum_{j=1}^{J} ODP_j \times B_j \qquad (\text{kg CFC-11}_{\text{-Eq.}}) \qquad \text{(A8)}$$

where:

ODP ozone depletion potential (kg CFC-$11_{\text{-Eq.}}$)

j ozone depleting substance (ODS) j (-)

J total number of ozone depleting substances (-)

ODP_j ozone depleting potential of substance j (kg CFC-11$_{\text{-Eq.}}$/kg ODS)

B_j amount of substance j emitted (kg ODS).

Photochemical oxidant creation potential (POCP)

This measured the potential for volatile organic compounds (VOCs) and NO_x to generate photochemicals, or summer smog, and is measured in kg ethylene (C_2H_4) equivalent (Heijungs et al., 1992). Photochemicals are hazardous to human health and can cause respiratory problems and cancer (EPA, 2004). C_2H_4 is used as the benchmark as its chemical degradation pathways are well defined and it is one of the more important ground level ozone forming species, with a low molecular weight (Derwent et al., 2010). The POCP is calculated from (Azapagic et al., 2011):

$$POCP=\sum_{j=1}^{J} POCP_j \times B_j \qquad \text{(kg } C_2H_{4\text{-Eq.}}\text{)} \qquad \text{(A9)}$$

where:

$POCP$ photochemical oxidant creation potential (kg $C_2H_{4\text{-Eq.}}$)

j ozone creating substance j (-)

J total number of ozone creating substances (-)

ODP_j photochemical oxidant creation potential of substance j (kg $C_2H_{4\text{-Eq.}}$/kg substance)

B_j amount of ozone creating substance j emitted (kg substance).

Human toxicity potential (HTP)

The HTP measures the potential for the release of substances toxic to human health, such as heavy metals and carcinogens into air, water and soil and is measured in kg 1-4-dichlorobenzene (DCB) equivalent (Heijungs et al., 1992). DCB was first used as a benchmark by Guinee et al for measuring toxicity and was selected because it is a well-studied substance that is moderate in both persistence and toxicity (Guinée et al., 1996). The benchmark has been used since. The HTP is calculated from (Azapagic et al., 2011):

$$HTP=\sum_{j=1}^{J} HTP_j \times B_j \qquad \text{(kg DCB}_{\text{-Eq.}}\text{)} \qquad \text{(A10)}$$

where:

HTP human toxicity potential (kg DCB$_{\text{-Eq.}}$)

j toxic substance j (-)

J total number of toxic substances (-)

HTP_j human toxicity potential of substance j (kg $DCB_{-Eq.}$/kg substance)

B_j amount of substance j emitted (kg substance).

Ecotoxicity potentials

The ecotoxicity potentials measure the release of substances toxic to aquatic and terrestrial environments and is measured in kg DCB equivalent (Guinee et al benchmark, see *HTP* for explanation) (Azapagic et al., 2011; Guinée et al., 1996). The aquatic environments considered are freshwater and marine, so three biomes are considered: freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP) and terrestrial ecotoxicity potential (TETP), which are calculated from (Azapagic et al., 2011):

$$FAETP=\sum_{j=1}^{J} FAETP_j \times B_j \qquad \text{(kg } DCB_{-Eq.}\text{)} \qquad \text{(A11)}$$

where:

$FAETP$ freshwater aquatic ecotoxicity potential (kg $DCB_{-Eq.}$)

j toxic substance j (-)

J total number of toxic substances (-)

$FAETP_j$ freshwater aquatic ecotoxicity potential of substance j (kg $DCB_{-Eq.}$/kg substance)

B_j amount of substance j emitted (kg substance).

$$MAETP=\sum_{j=1}^{J} MAETP_j \times B_j \qquad \text{(kg } DCB_{-Eq.}\text{)} \qquad \text{(A12)}$$

where:

$MAETP$ marine aquatic ecotoxicity potential (kg $DCB_{-Eq.}$)

j toxic substance j (-)

J total number of toxic substances (-)

$MAETP_j$ marine aquatic ecotoxicity potential of substance j (kg $DCB_{-Eq.}$/kg substance)

B_j amount of substance j emitted (kg substance).

$$TETP=\sum_{j=1}^{J} TETP_j \times B_j \qquad \text{(kg DCB}_{\text{-Eq.}}\text{)} \qquad \text{(A13)}$$

where:

TETP terrestrial ecotoxicity potential (kg $DCB_{-Eq.}$)

j toxic substance j (-)

J total number of toxic substances (-)

$TETP_j$ terrestrial ecotoxicity potential of substance j (kg $DCB_{-Eq.}$/kg substance)

B_j amount of substance j emitted (kg substance).

AV. Life cycle inventory data

In this study, secondary data from the Ecoinvent V2.2 database and literature were used to model UK shale gas extraction and use to generate electricity (Ecoinvent Centre, 2010). The shale gas well and gas extraction process is modelled using data collected from SONRIS (Strategic Online Natural Resources Information System), Ceres, FracFocus, Cuadrilla and other sources:

- well size;
- material requirements for the well;
- drilling fluid requirements;
- fracturing fluid volume and composition;
- hydraulic fracturing power requirements;
- shale gas composition; and
- volume of gas produced (estimated ultimate recovery, EUR).

The well sizes and EURs are calculated using data from SONRIS, where data from over 2,300 wells in the Haynesville shale play in Louisiana State was collected (SONRIS, 2013). Out of all the major US shale plays, this one is the most similar in depth to the Bowland-Hodder shale play in the UK (Clarke et al., 2014; Kaiser and Yu, 2011). Therefore, it is assumed that well sizes and material requirements would be appropriate for modelling shale gas extracted in the UK. The amount of steel and cement used per well is calculated from this information, as was the diameter and depths of the wellbores. This allowed steel casing, cement and drilling fluid requirements to be calculated, as well as the amount of drilling waste generated.

The annular capacity of the wellbore is used to calculate the amount of solid waste generated, from which the total waste (liquid and solid) generated is calculated. The calculation method used for this can be found in Appendix B. When this is calculated, American Petroleum Institute (API) estimates and ratios are used to calculate the total amount of waste generated (Ford and Veil, 2003; Geehan et al., 1990). For waste disposal, API data for waste treatment is used to split disposal into three categories (API, 2000): landfill, land spreading and incineration. The drilling fluid used is modelled on data from Deville et al. (2011)(water based mud, WBM) and Russell and Hargreaves (2013) (oil based mud, OBM).

From the data collected, WBM is found to be the more commonly used drilling fluid and is therefore used in the GaBi models. An alternative to WBM is OBM, which is better suited for drilling to the depths at which shale gas containing rock is found, as well as directional drilling. However, it is more expensive and (traditionally) more toxic as mineral oils and diesel can be used as the carrier fluid. They are also subject to more stringent disposal regulations, which is why WBM are often favoured. There is evidence that OBM will be used in the UK for shale gas drilling as both iGas and Cuadrilla have published documents stating they intended to use OBM in their drilling (Arup, 2014; Russell and Hargreaves, 2013). Therefore a sensitivity analysis will be conducted to compare the two.

To model hydraulic fracturing, the volume and composition of fracturing fluid is needed, as well as the pumping power required. The volume of water used is collected from FracFocus and Ceres while the composition is based on data from Cuadrilla. The pumping power is calculated from the power rating of pumping equipment used and the amount of time spent hydraulically fracturing a well. From the literature, the average power rating of equipment is 1.86 MW (2,500 HP) (Trican, 2014). Hydraulically fracturing a well occurs in stages of 1,000 ft (304 m), which take two hours to complete (Clark et al., 2013; Stephenson et al., 2011).

The amount of gas produced by a well is estimated as the EUR, which is an estimation of the total amount of gas extracted over the well's lifespan. The calculations for this can be found in Appendix B. The average and maximum EURs calculated are used in GaBi; the minimum economic EUR (from literature) was used instead of the calculated minimum (Cohen, 2013), on account of it being five orders of magnitude smaller than the maximum. From the EUR calculations, fugitive methane emissions are calculated. The API estimate for average onshore gas production losses was used in GaBi (0.17% of the EUR (API, 2000)). A sensitivity analysis based on fugitive emissions is also conducted, as this is a grey area in the literature (accurate fugitive emission quantification) and high emissions can negate benefits of fuel switching over coal, as methane is a more potent GHG than CO_2 (Blasing, 2016). The minimum emissions is set at zero, implying green completion is used (no gas vented or flared) and a maximum of 312,000 m^3 is used, which is the EPA's estimate of methane losses in shale gas completion (EPA, 2012).

When the shale gas model is built in GaBi, it can be integrated into a shale gas for electricity model. For this, Ecoinvent V2.2 datasets are used. Data from The Department of Energy and Climate Change (DECC) on CCGT power plant efficiency is used to modify the power plant dataset (DECC, 2013). When the model is built, the environmental impacts can be calculated in GaBi. The same procedure is carried out for the other electricity options. The Ecoinvent datasets are used, with DECC data to modify datasets to make them more representative of UK 2012 conditions. The GaBi models of electricity options are then used to model the UK electricity mix.

AVI. Economic sustainability assessment

The life cycle cost (LCC) is the sum of all the funds expended to support a product or service in a specified system boundary (Ciroth et al., 2008; Fuller and Petersen, 1996; Swarr et al., 2011). The tool is based purely on financial valuation and includes investment, operation and management and end-of-life expenses. Other methods of economic valuation are payback, savings to interest ratio and rate of return (Ciroth et al., 2008; Swarr et al., 2011). LCC is advantageous over other methods as all the costs of a product incurred over its entire life cycle are integrated (Ciroth et al., 2008; Davis Langdon Management Consulting, 2007; Fuller and Petersen, 1996; Swarr et al., 2011). It can also be carried out following the same procedures used for LCA, but the scope is different as the costs, rather than the environmental impacts, are of interest and the goal of LCC is to estimate the costs associated with the existence of a product.

Unlike LCA, there is no standardised procedure for LCC and as a result, there are many methods that can be used to calculate it, including net present value and levelised cost (Huppes et al., 2004), which have been used to estimate the life cycle cost of electricity generated from shale gas. The economic sustainability is assessed by evaluating the economic viability of UK shale gas, which is judged on the basis of whether or not it can compete with other gas and other electricity options. The LCC of shale gas is used to estimate the cost of producing shale gas while the LCC of shale gas electricity is used to estimate the cost of generating electricity from it. The LCC is calculated for two system boundaries: 'cradle to gate' and 'cradle to grave'. The two system boundaries are used as shale gas is a fuel itself which can be used to generate electricity and, therefore, can compete in two markets: natural gas and electricity. In order for shale gas to be competitive, the cost of producing it must be lower than current market gas prices and the cost of generating electricity from shale gas must be lower than other electricity options, such as wind, solar and nuclear. If this is found to be the case, then UK shale gas is viable and can be seen as economically sustainable. On the other hand, if this is not found to be the case then shale gas is not viable and not economically sustainable.

AVII. Social sustainability assessment

Social sustainability is the sphere of sustainability which regards impacts to society. In comparison to environmental and economic sustainability, it is less well defined and studied. There is no standardised procedure for how to assess it (Mohan, 2015; Oyevaar et al., 2016) and there is a high level of uncertainty in terms of how to assess it. Consequentially, there are numerous metrics which can be used to measure social sustainability. However, many focus on one stage and aspect; whereas this study aims to assess the life cycle impacts of UK shale gas extraction and use for electricity generation. To assess the social sustainability of shale gas and use for electricity generation, a social sustainability assessment was conducted.

In total 14 indicators are used to assess the social sustainability and impacts to communities. The results calculated are used to determine what benefits, and to what scale, are created as a direct result of UK shale gas extraction and use. The results are also used to assess whether there were any burdens created as a result of development.

AVIII. Multi-criteria decision analysis

The three aspects of sustainability need to be integrated in order to assess the overall sustainability. To conduct this assessment, the results of the LCA, LCC and social sustainability assessment are combined and used in a decision analysis to determine whether or not shale gas electricity in the UK is sustainable. For this a multi-criteria decision analysis (MCDA) is conducted. The MCDA has three criteria: environmental, economic and social, which each contain their own indicators for assessment.

This method is used for this assessment because it is a tool suited for complex decision making problems (Azapagic and Perdan, 2005a; Azapagic and Perdan, 2005b). MCDA is particularly useful for problem scenarios which involve complex and conflicting criteria, as well as numerous options to select from, because it compares them against one other on the criteria specified, allowing them to be ranked based on their performance (Azapagic and Perdan, 2005a; Azapagic and Perdan, 2005b). To conduct an MCDA, the practitioner must specify the options to be compared and the criteria they are to be compared on. The practitioner (or the decision maker) then sets the preferences for the criteria and indicators, which are used in combination with the performance of the options to determine which is better. There are many methods available for conducting MCDA but in principle there are two families; multi-objective decision analysis (MODA) and multi-attribute decision analysis (MADA) (Azapagic and Perdan, 2005a; Azapagic and Perdan, 2005b). MODA methods aim to find the optimum option while MADA aims to create a hierarchy of the options (Azapagic and Perdan, 2005a; Azapagic and Perdan, 2005b). As this work aims to determine whether or not shale gas is sustainable, it needs to be compared with other electricity options and therefore MADA is the most appropriate method.

Multi-attribute utility theory (MAUT) is a MADA method which compares options using utility (or value) functions: a mathematical function which converts preferences into numerical values allowing real numbers to be associated with options and criteria (Barford and Leleur, 2014). MAUT is one of the most commonly used MADA methods because of its simplicity to conduct and the practitioner is not restricted to the number of alternative or criteria they can consider (Azapagic and Perdan, 2005a; Azapagic and Perdan, 2005b). Simple multi-attribute rating technique (SMART) is the simplest form of MAUT.

In the SMART method, the options are ranked based on criteria specified, be it indicators or aspects. The aspects/indicators are weighted based on their relative importance to one another. The least important is allocated a score of 10 with higher scored given to more important aspects/indicators. The options are also rated based on how well they perform in the indicators specified through the use of value functions. The options are given a rating (between zero and one) based on how well they perform in a given indicator. The worst performing is rated zero while the best is rated one. The remaining options are given intermediate ratings based on where they lie between the best and worst options and this rating affected by the type of value function used, as shown in Figures A12 and A13. It should be noted that the weightings applied are subjective to the preferences of the stakeholders or the MCDA practitioner. The variation in subjectivity has been assessed through the range of weightings applied in the sensitivity analysis in Chapter 6.

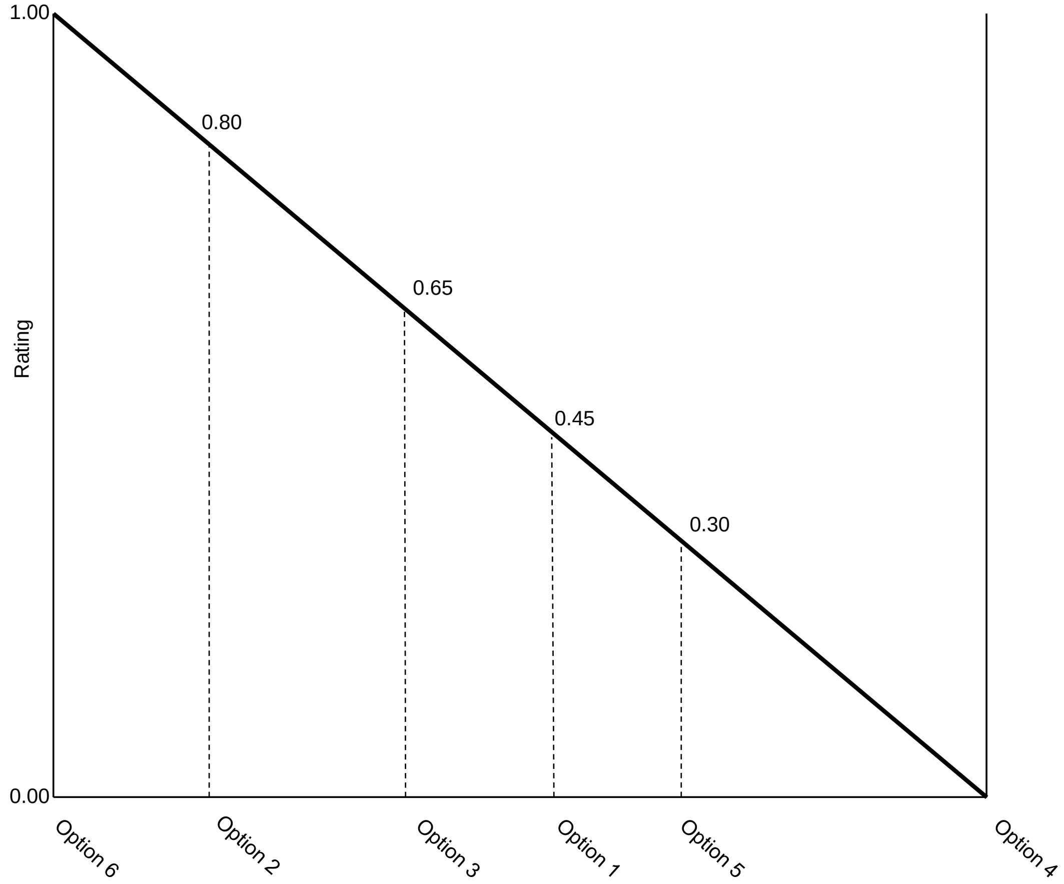


Figure A12: Rating of options using a linear value function.

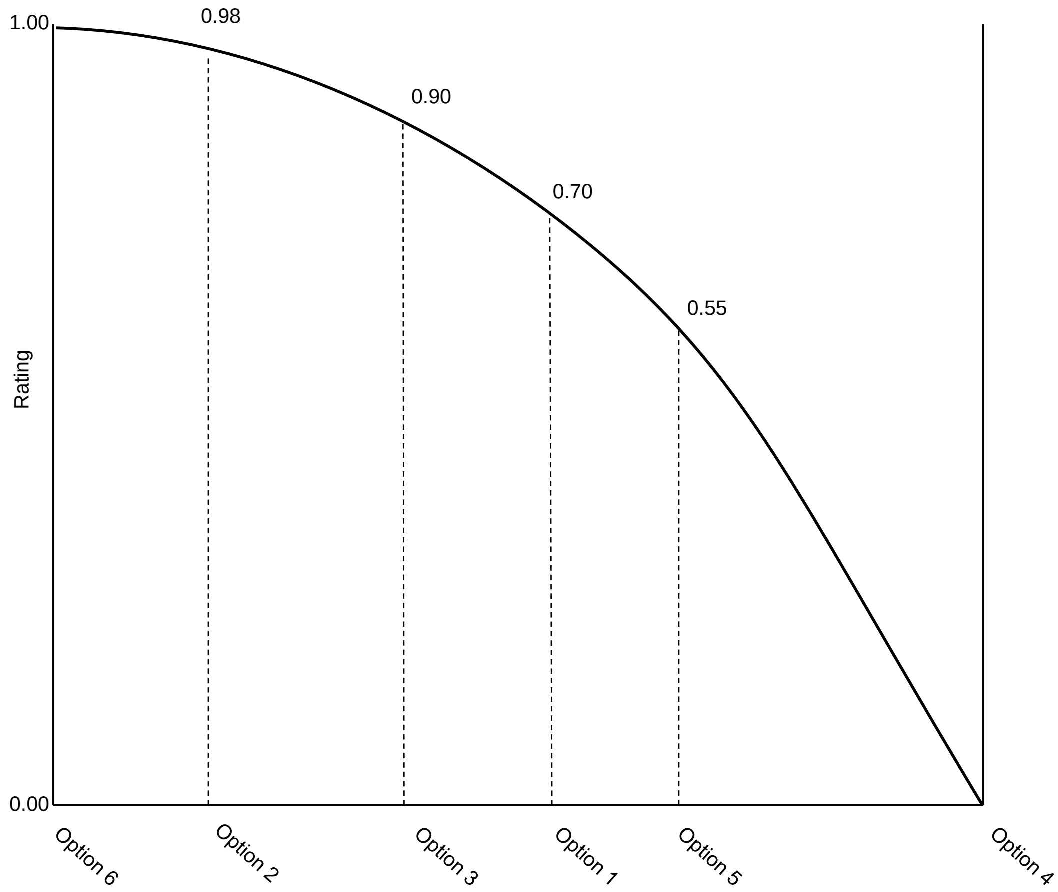


Figure A13: Rating of options using an exponential value function.

Nomenclature

ADP_e elemental resource depletion potential (kg $Sb_{-Eq.}$)

$ADP_{e,j}$ elemental resource depletion potential of resource j (kg $Sb_{-Eq.}$/kg resource)

ADP_f fossil fuel resource depletion potential (MJ)

$ADP_{f,j}$ fossil fuel resource depletion potential of resource j (MJ/kg resource)

AP: acidification depletion potential (kg $SO_{2-Eq.}$)

AP_j acidification potential of gas j (kg $SO_{2-Eq.}$/kg gas)

$b_{j,I}$ burden j for activity i

B_j burden

$e_{k,j}$ characterisation factor, representative of contribution of burden B_j towards impact E_k

E_k environmental impact

EP eutrophication depletion potential (kg $PO_4^{3-}{}_{Eq.}$)

EP_j eutrophication depletion potential of nutrient j (kg $PO_4^{3-}{}_{Eq.}$/kg nutrient)

$FAETP$ freshwater aquatic ecotoxicity potential (kg $DCB_{-Eq.}$)

$FAETP_j$ freshwater aquatic ecotoxicity potential of substance j (kg $DCB_{-Eq.}$/kg substance)

GWP global warming potential (kg $CO_{2-Eq.}$)

GWP_j global warming potential of greenhouse gas j (kg $CO_{2-Eq.}$/kg greenhouse gas)

HTP human toxicity potential (kg $DCB_{-Eq.}$)

HTP_j human toxicity potential of substance j (kg $DCB_{-Eq.}$/kg substance)

i activity

j burden category e.g. emission of CO_2.

k impact category e.g. global warming, ozone depletion, water toxicity etc.

$MAETP$ marine aquatic ecotoxicity potential (kg $DCB_{-Eq.}$)

$MAETP_j$ marine aquatic ecotoxicity potential of substance j (kg $DCB_{-Eq.}$/kg substance)

ODP ozone depletion potential (kg CFC-$11_{-Eq.}$)

ODP_j ozone depleting potential of substance j (kg CFC-$11_{-Eq.}$/kg ODS)

$POCP$ photochemical oxidant creation potential (kg $C_2H_{4-Eq.}$)

$PODP_j$ photochemical oxidant creation potential of substance j (kg $C_2H_{4-Eq.}$/kg substance)

$TETP$ terrestrial ecotoxicity potential (kg $DCB_{-Eq.}$)

$TETP_j$ terrestrial ecotoxicity potential of substance j (kg $DCB_{-Eq.}$/kg substance)

z_i mass or energy flow of activity i

References

API. **2000**. *Overview of exploration and production waste volume and waste management practices in the United States*. *American Petroleum Institute (API)*. Washington DC. Retrieved from: http://www.api.org/~/media/files/ehs/environmental_performance/icf-waste-survey-of-eandp-wastes-2000.pdf?la=en.

Arup. **2014**. *Temporary Shale Gas Exploration at Roseacre Wood, Lancashire- Environmental Statement- Volume 1*. *Cuadrilla Elswick Ltd*. Preston, UK. Retrieved from: http://www.cuadrillaresources.com/our-sites/locations/roseacre-wood/.

Azapagic, A. and Perdan, S. **2005a**. An integrated sustainability decision-support framework Part I: Problem structuring. *International Journal of sustainable Development and World Ecology*, 12, 98-111.

Azapagic, A. and Perdan, S. **2005b**. An integrated sustainability decision-support framework Part II: Problem analysis. *International Journal of Sustainable Development and World Ecology*, 12, 112-131.

Azapagic, A., Perdan, S., Krewitt, W., Muller-Stichnithe, H., Darton, R., Pehnt, M., Stichnothe, H., Espinoza-Orias, N., Fenner, R., Flores, A., Bows, A., Anderson, K., Chalabi, Z. and Fletcher, T. **2011**. *Sustainable development in practice: Case studies for engineers and scientists*, Chichester, UK: Wiley-Blackwell.

Barford, M. B. and Leleur, S. **2014**. *Multi-criteria decision analysis for use in transport decision making*. *Technical University of Denmark*. Lyngby, DK. Retrieved from: http://orbit.dtu.dk/en/publications/multicriteria-decision-analysis-for-use-in-transport-decision-making(aa15f7cc-eb6b-4ca4-ab79-994453751544).html.

Baumann, H. and Tillman, A.-M. **2004**. *The hitch hiker's guide to LCA*, Lund, SE: Studentlitteratur.

BBC Nature. **2016**. *History of life on Earth* [Online] London, UK: The British Broadcasting Corporation (BBC). Available: http://www.bbc.co.uk/nature/history_of_the_earth/ [Accessed April 2016].

Blasing, T. J. **2016**. *Recent greenhouse gas concentrations*. *Carbon Dioxide Information Analysis Centre (CDIAC)*. Oak Ridge, TN, USA. Retrieved from: http://cdiac.ornl.gov/pns/current_ghg.html.

Ciroth, A., Huppes, G., Klopffer, W., Rudenauer, I. and Swarr, T. **2008**. *Environmental life cycle costing*, Brussels, BE: Society of Environmental Toxicology and Chemistry (SETAC).

Clark, C., Burnham, A., Harto, C. and Horner, R. **2013**. *Hydraulic fracturing and shale gas production: Technology, impacts, and regulations*. *Argonne National Laboratory*.

Oak Ridge, TN, USA. Retrieved from: http://www.afdc.energy.gov/uploads/publication/anl_hydraulic_fracturing.pdf.

Clark, C., Han, J., Burnham, A., Dunn, J. B. and Wang, M. Q. **2011**. *Life-cycle analysis of shale gas and natural gas*. *Argonne National Laboratory*. Lemont, IL, USA. Retrieved from: https://greet.es.anl.gov/publication-shale_gas.

Clarke, H., Turner, P. R. and Bustin, M. **2014**. *Unlocking the resource potential of the Bowland Basin, NW England (Conference)*. SPE/EAGE European Unconventional Resources Conference and Exhibition. 25-27 February 2014 Vienna, AT. Society of Petroleum Engineers (SPE).

Cohen, H. K. **2013**. *The shale gas paradox: Assessing the impacts of the shale gas revolution on electricity markets and climate change*. Bachelor, Harvard College.

Davis Langdon Management Consulting. **2007**. *Life cycle costing (LCC) as a contribution to sustainable construction: a common methodology*. *European Commission*. London, UK. Retrieved from: http://ec.europa.eu/DocsRoom/documents/5054/attachments/1/translations/en/renditions/native.

DECC. **2013**. *Digest of United Kingdom energy statistics 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/279523/DUKES_2013_published_version.pdf.

Derwent, R. G., Jenkin, M. E., Pilling, M. J., Carter, W. P. and Kaduwela, A. **2010**. Reactivity scales as comparative tools for chemical mechanisms. *J Air Waste Manag Assoc*, 60, 914-24.

Deville, J. P., Fritz, B. and Jarrett, M. **2011**. Development of water-based drilling fluids customized for shale reservoirs. *SPE Drilling and Completion*, 26, 484-491.

Ecoinvent Centre. **2010**. *Ecoinvent datadata v2.2.* Zurich, CH Retrieved from: http://www.ecoinvent.org/database/.

EPA. **2004**. *Photochemical smog- what it means for us*. *US Environmental Protection Agency (EPA)*. Washington DC. Retrieved from: www.epa.sa.gov.au/files/8238_info_photosmog.pdf.

EPA. **2012**. *Oil and natural gas sector: Standard of performance for crude oil and natural gas production, transmission, and distribution*. *US Environmental Protection Agency (EPA)*. Washington DC. Retrieved from: https://www3.epa.gov/airquality/oilandgas/pdfs/20120418tsd.pdf.

EPA. **2016a**. *Effects of acid rain* [Online] Washington DC: US Environmental Protection Agency (EPA). Available: https://www.epa.gov/acidrain/effects-acid-rain [Accessed April 2016].

EPA. **2016b**. *Health and environmental effects of ozone layer depletion* [Online] Washington DC: US Environmental Protection Agency (EPA). Available:

https://www.epa.gov/ozone-layer-protection/health-and-environmental-effects-ozone-layer-depletion [Accessed April 2016].

Ford, J. and Veil, J. **2003**. *An introduction to slurry injection technology for disposal of drilling waste*. *Argonne National Laboratory*. Oak Ridge, TN, USA. Retrieved from: http://www.veilenvironmental.com/publications/oil/brochure-final-1628.pdf.

Fuller, S. K. and Petersen, S. R. **1996**. *Life-cycle costing manual for the Federal energy management program*. *US Department of Energy*. Washington DC. Retrieved from: https://www.wbdg.org/ccb/NIST/hdbk_135.pdf.

Geehan, T., Helland, B., Maddin, C. and Page, W. **1990**. Reducing the oilfield's environmental footprint. *Oilfield Review*, 2, 53-63.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. D., Struijs, J. and van Zelm, R. **2013**. *ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint*. *Rijksinstituut voor Volksgezondheid en Milieu (RIVM)*. Bilthoven. Retrieved from: http://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf.

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H. A., de Bruijn, H., van Duin, R. and Huijbregts, M. A. J. **2002**. *Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background*, Dordrecht, NL: Kluwer Academic Publishers.

Guinee, J. B. and Heijungs, R. October 2013 *2013*. RE. *ResearchGate message* to J. Cooper.

Guinée, J. B., Heijungs, R., Oers, L. v., Meent, D. v. d., Vermeire, T. and Rikken, M. **1996**. *LCA impact assessment of toxic releases: Generic modelling of fate, exposure and effect for ecosystems and human beings with data for about 100 chemicals*. *Centre of Environmental Science (CML), Leiden University*. Leiden, NL. Retrieved from: http://www.rivm.nl/Documenten_en_publicaties/Wetenschappelijk/Wetenschappelijke_artikelen/1996/juli/LCA_impact_assessment_of_toxic_releases_Generic_modelling_of_fate_exposure_and_effect_for_ecosystems_and_human_beings_with_data_for_about_100_chemicals.

Hall, J., Dore, A., Heywood, E., Broughton, R., Stedman, J., Smith, R. and O'Hanlon, S. **2006**. *Assessment of the environmental impacts associated with the UK Air Quality Strategy*. *Department for Environment Food and Rural Affairs (DEFRA)*. London, UK. Retrieved from: https://uk-air.defra.gov.uk/assets/documents/reports/cat16/0604050845_CEH_AQS_FINALREPORT_04Apr2006.pdf.

Heijungs, R., Guinée, J. B., Huppes, G., Lankreijer, R. M., Udo de Haes, H. A., Wegener Sleeswijk, A., Ansems, A. M. M., Eggels, P. G., Duin, R. v. and Goede, H. P. d.

1992. *Environmental life cycle assessment of products: guide and backgrounds (Part 1)*. *Centre of Environmental Science (CML), Leiden University*. Leiden. Retrieved from: https://openaccess.leidenuniv.nl/handle/1887/8061.

Huppes, G., Rooijen, M. v., Kleijn, R., Heijungs, R., Koning, A. d. and Oers, L. v. **2004**. *Life cycle costing and the environment Dutch National Institute for Public Health and the Environment (RIVM)*. Bilthoven, NL. Retrieved from: http://www.rivm.nl/Onderwerpen/L/Life_Cycle_Assessment_LCA/ReCiPe/Publicaties.

IINAS. **2017.** GEMIS- Global emissions model for integrated systems IINAS (International Institute for Sustainability Analysis and Strategy),: Darmstadt, DE.

ISO. **2006a**. *EN ISO 14040: 2006 Environmental management - Life cycle assessment - Principles and framework*. International Organization for Standardization (ISO). Geneva, CH.

ISO. **2006b**. *EN ISO 14044:2006 Environmental management - Life Cycle assessment - Requirements and guidelines*. International Organization for Standardization (ISO). Geneva, CH.

Kaiser, M. J. and Yu, Y. **2011**. Louisiana Haynesville Shale -1: Characteristics, production potential of Haynesville shale well described. *Oil and Gas Journal* [Online], 109. Available: http://www.ogj.com/1/vol-109/issue-49/exploration-development/louisiana-haynesville-shale-full.html [Accessed: April 2017].

Kissinger, A., Helmig, R., Ebigbo, A., Class, H., Lange, T., Sauter, M., Heitfeld, M., Klünker, J. and Jahnke, W. **2013**. Hydraulic fracturing in unconventional gas reservoirs: risks in the geological system, part 2. *Environmental Earth Sciences*, 70, 3855-3873.

Mohan, B. **2015**. *Global frontiers of social development in theory and practice: Climate, economy and justice*, First, New York, NY, USA: Palgrave Macmillan.

Oyevaar, M., Vazquez-Brust, D. and Bommel, H. v. **2016**. *Globalization and sustainable development: A business perspective*, London, UK: Palgrave.

PE. **2012**. *GaBi Manual*. *PE International*. Stuttgart, DE. Retrieved from: http://www.gabi-software.com/fileadmin/GaBi_Manual/GaBi_6_manual.pdf.

Russell, C. and Hargreaves, T. R. **2013**. *Permit application: Irlam wells waste management plan*. *IGas Energy Plc*. Manchester, UK. Retrieved from: https://www.whatdotheyknow.com/request/205082/response/511630/attach/6/IRLM%20EPA%20008.pdf.

Smith, V. H., Tilman, G. D. and Nekola, J. C. **1999**. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution*, 100, 179 - 196.

SONRIS. **2013**. *Well Information.* Strategic Online Natural Resources Information System (SONRIS): Baton Rouge, LA, USA (March 2014) Retrieved from: http://sonlite.dnr.state.la.us/sundown/cart_prod/cart_con_wellinfo1.

Stephenson, T., Valle, J. E. and Riera-Palou, X. **2011**. Modeling the Relative GHG Emissions of Conventional and Shale Gas Production. *Environmental Science and Technology*, 45, 10757-10764.

Swarr, T. E., Hunkeler, D., Klopffer, W., Pesonen, H.-L., Ciroth, A., Brent, A. C. and Pagan, R. **2011**. Environmental life-cycle costing: a code of practice. *The International Journal of Life Cycle Assessment*, 16, 389-391.

Thermidaire. **2014**. *pH Calculator* [Online] Mississauga, ON, CA: Thermidaire Corporation Canada Limited. Available: http://www.thermidaire.on.ca/pc.html [Accessed April 2014].

thinkstep. **1992-2016.** GaBi software-system and database for life cycle engineering *6.115 6.115* thinkstep AG: Stuttgart, DE.

Trican. **2014**. *Hydraulic Fracturing* [Online] Calgary, AB, CA: Trican. Available: http://www.tricanwellservice.com/fracturing [Accessed February 2014].

van Oers, L., de Koning, A., Guinee, J. B. and Huppes, G. **2002**. *Abiotic resource depletion in LCA*. *Road and Hydraulic Engineering Institute*. Leiden, NL. Retrieved from: http://www.leidenuniv.nl/cml/ssp/projects/lca2/report_abiotic_depletion_web.pdf.

WMO. **2012**. *Scientific assessment of ozone depletion: 2010*. *World Meteorological Organization, Global Ozone Research and Monitoring Project*. Geneva, Switzerland. Retrieved from: http://www.wmo.int/pages/prog/arep/gaw/ozone_2010/ozone_asst_report.html.

Appendix B

BI. Data for different well sizes

Tables S1-S9 refer to the data from SONRIS (SONRIS, 2013) for 2386 wells in the Haynesville shale play, which have been used to calculate the average well sizes and other parameters; these have been used for the central case in the analysis. The minimum and maximum values across the wells represent the best and worst case, respectively. Tables B1 to B3 show the average values (central case), tables B4 to B6 the minimum (best case) and B7 to B9 the maximum values (worst case).

BI.I Average size

Table B1. Average size of the well[a] (SONRIS, 2013).

	Depth/length (m)
True vertical depth	3,660
True measured depth	5,080
Perforation length	1,290

[a] Estimated based on the size of 2386 wells.

Table B2. Steel casing dimensions and steel requirements for the average size well (SONRIS, 2013).

Casing	Inner diameter (m)	Outer diameter (m)	Thickness (mm)	Length (m)	Steel (tonnes)
Conductor[a]	0.273	0.318	44.8	15.2	1.03
Surface[b]	0.194	0.253	59.1	152	6.74
Intermediate[c]	0.219	0.175	44.5	305	14
Production[d]	0.140	0.119	21.1	1790	61

[a] First (outer) layer casing to prevent loose soil at and near the surface from collapsing.
[b] Second layer casing to protect surface water.
[c] Third layer casing to prevent the borehole caving in.
[d] Final (inner) layer that forms the outer boundary of the annulus.

Table B3. Cement requirements for the average size well[a] (SONRIS, 2013).

Casing	Wellbore diameter (m)[b]	Cement (tonnes)
Conductor	0.419	57
Surface	0.343	168
Intermediate	0.251	168
Production	0.172	38

[a] Cement is used to strengthen the steel casing and integrity of the well.
[b] The borehole is wider than the steel casing outer diameter in Table B2 to make sure that it can be installed easily; the gap between the casing and the soil/rock is sealed with cement.

BI.II. Minimum size

Table B4. Minimum size of the well (SONRIS, 2013).

	Depth/length (m)
True vertical depth	2,760
True measured depth	3,230
Perforation length	4.27

Table B5. Steel casing for the minimum size of the well (SONRIS, 2013).

Casing	Inner diameter (m)	Outer diameter (m)	Thickness (mm)	Length (m)	Steel (tonnes)
Conductor	0.273	0.318	44.8	15.2	10.3
Surface	0.194	0.253	59.1	152	6.74
Intermediate	0.175	0.219	44.5	305	14
Production	0.119	0.140	21.1	514	18

Table B6. Cement requirements for the minimum size well (SONRIS, 2013).

Cement	Wellbore diameter (m)	Cement (tonnes)
Conductor	0.419	57
Surface	0.343	77
Intermediate	0.251	77
Production	0.172	9

BI.III. Maximum size

Table B7. Maximum size of the well (SONRIS, 2013).

	Depth/length (m)
True vertical depth	5,070
True measured depth	6,290
Perforation length	2,420

Table B8. Steel casing for the maximum size well (SONRIS, 2013).

Casing	Inner diameter (m)	Outer diameter (m)	Thickness (mm)	Length (m)	Steel (tonnes)
Conductor	0.273	0.318	44.8	15.2	1.03
Surface	0.194	0.253	59.1	152	6.74
Intermediate	0.175	0.219	45.5	305	14
Production	0.119	0.140	21.1	2930	100

Table B9. Cement requirements for maximum size well (SONRIS, 2013).

Cement	Wellbore diameter (m)	Cement (tonnes)
Conductor	0.419	57
Surface	0.343	168
Intermediate	0.251	168
Production	0.171	919

BII. Drilling fluid and waste

The amount of solid (drill cuttings) drilling waste, W_{cg}, was estimated based on the annular capacity of the well, *Ch,* using the following equations (Lapeyrouse, 2002):

$$Ch=\frac{D^2}{1029.4} \qquad (m^2) \qquad (B1)$$

$$W_{cg}=350\ Ch\ x\ L\ x\ (1-P)\ x\ SG \qquad (kg) \qquad (B2)$$

where:

D wellbore diameter (m)

L length drilled (m)

P porosity of cuttings (-)

SG specific gravity of the cuttings (kg/m^3).

The amount of solid and liquid drilling waste is given in Table B10.

Table B10. Drilling waste generated over the lifetime of the well.

	Annular capacity (bbl/m)	Solid waste[a] (kt)	Liquid waste[b] (kt)	Total drilling waste (kt)
Central case (average)	1.9	0.7	17.3	18.0
Best case (minimum)	1.9	0.2	10.6	10.9
Worst case (maximum)	1.9	1.1	21.7	22.7

[a] Estimated by equation (B2).
[b] Assumed to be equal to the amount of drilling fluid used.

Table B11. Oil-based fluid composition (Russell and Hargreaves, 2013).

Component	Composition (% w/w)
Mineral oil	36.3
Water	30.2
Barite	16.1
Calcium chloride	10.7
Emulsifiers	2.8
Lime	1.3
Clay	1.3
Asphalt	1.3

BIII. Shale gas composition

The composition of shale gas is based on the average USA shale gas composition, as shown in Table B12.

Table B12. Shale gas composition (George and Bowles., 2011).

Component	Marcellus (vol %)	Appalachia (vol %)	Haynesville (vol %)	Eagle Ford (vol %)	Barnett (vol %)	Average (vol %)
Methane	97.131	79.085	96.323	74.596	86.75	86.777
Ethane	2.44	17.705	1.084	13.824	6.725	8.250
Propane	0.095	0.566	0.205	5.425	1.975	1.653
Butane	0.014	0.034	0.203	4.462	0.000	0.943
Pentane	0.001	0.000	0.061	0.478	0.000	0.108
Carbon dioxide	0.040	0.073	1.816	1.536	1.675	1.028
Nitrogen	0.279	2.537	0.369	0.157	2.875	1.243

BIV. Estimated ultimate recovery

The estimated ultimate recovery (EUR) has been calculated using data for the initial (first month's) production for 2,386 shale gas wells in the SONORIS database (SONRIS, 2013), assuming the hyperbolic decline rate of production (Symmons et al., 2010):

$$q(t) = \frac{q_i}{(1+bD_i t)^{1/b}} \quad (m^3/\text{month}) \quad \text{(B3)}$$

where:

$q(t)$ monthly production rate (m^3/month)

q_i initial production rate (m^3/month),

b Arps' decline exponent (-)

D_i initial decline constant (month^{-1}).

t month t (month)

The EUR is calculated by summing *q(t)* over the average lifespan of the well of 30 years (Clark et al., 2013). Values of *b* and *Di* were collected from the literature. As shown in Figure B1, there is a wide variation in the EUR.

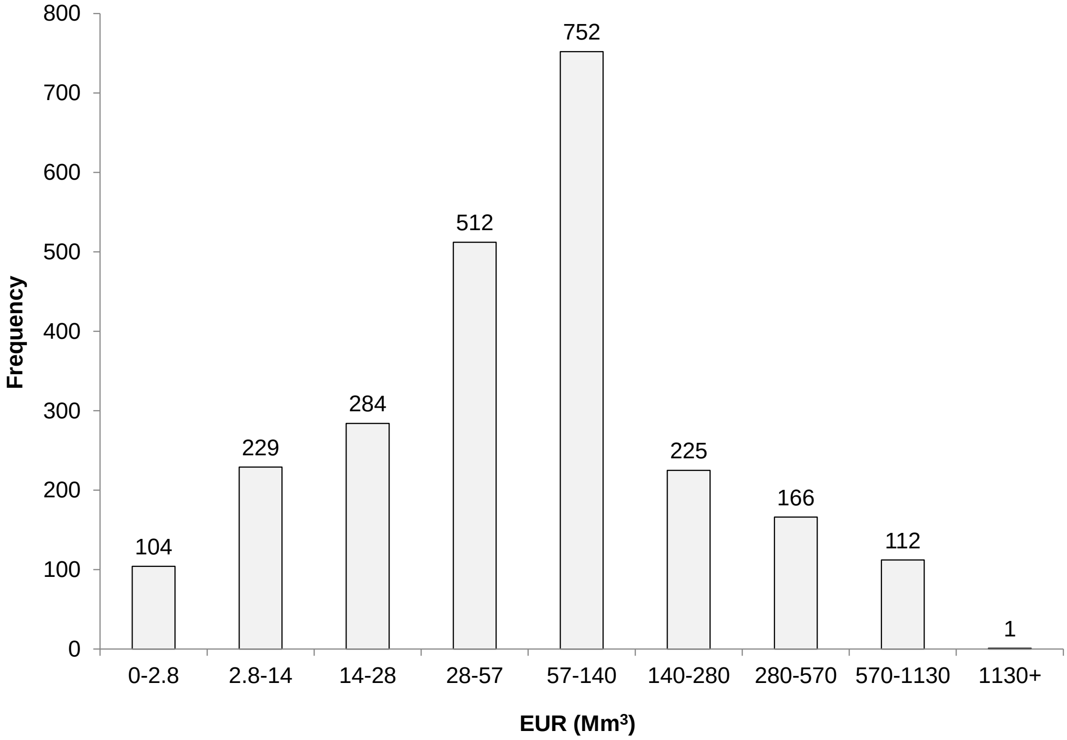


Figure B1. Distribution of EUR.

BV. Data used for LCA modelling

Tables B13 and B14 detail the data used in the LCA modelling of shale gas. These are based on the Ecoinvent data for an onshore natural gas well and onshore natural gas production which have been adapted to shale gas as follows. The amounts of steel, cement, drilling fluid, power for drilling and drilling waste are estimated in this work and Ecoinvent data used to calculate the LCA impacts from these inputs. The other parameters have been scaled relative to the amount of drilling mud (Table B13) and the length of the gas well (Table B14). It is necessary to scale the Ecoinvent data owing to the different sizes of the wells and has been carried out according to the equation typically used for cost scaling of process equipment (known as the 'economies of scale') (Towler and Sinnot, 2008):

$$C_2 = C_1 \left(\frac{c_2}{c_1}\right)^{0.6} \tag{B4}$$

where C_1 and C_2 are the amounts of materials and energy used for the larger and smaller well, respectively; c_1 and c_2 are the larger and smaller well capacities, respectively; 0.6 is the 'economy of scale' factor.

Table B13: Model data used for GaBi shale gas well.

Ecoinvent data[a]	Units	Average	Minimum	Maximum
CH: disposal, drilling waste, 71.5% water, to landfarming [landfarming]	kg	530	503	542
CH: disposal, drilling waste, 71.5% water, to residual material landfill [residual material landfill facility]	kg	2,550	2,410	2,600
CH: disposal, hazardous waste, 25% water, to hazardous waste incineration [hazardous waste incineration]	kg	460	436	470
CH: Portland cement, strength class Z 52.5, at plant [Binder]	kg	138	217	112
Drilling mud-JC [Appropriation]	kg	3,400	3,280	3,440
GLO: crude oil, used in drilling tests [Appropriation]	kg	30.1	29. 5	30.3
GLO: diesel, burned in diesel-electric generating set [fuels]	MJ	8,570	8,390	8,630
GLO: natural gas, vented [Appropriation]	Nm^3	41.0	5.36	340
Hydraulic fracturing [Appropriation]	m^3	0.208	0.306	0.162
RER: lubricating oil, at plant [organics]	kg	57.2	56.0	57.6
RER: reinforcing steel, at plant [Beneficiation]	kg	101	50.2	131
RER: transport, freight, rail [Railway]	t.km	464	454	468
RER: transport, lorry >16t, fleet average [Street]	t.km	77.3	75.7	77.9
Occupation, mineral extraction site [Hemeroby]	m^2yr	14.3	14.0	14.4
Transformation, from forest [Hemeroby]	m^2	85.7	84.0	86.4
Transformation, to mineral extraction site [Hemeroby]	m^2	85.8	84.0	86.4

[a] Land spreading is labelled as landfarming in the dataset.

Table B14: Model data used in GaBi for natural gas extraction.

Ecoinvent data	Units	Average	Minimum	Maximum
CH: disposal, antifreezer liquid, 51.8% water, to hazardous waste incineration [hazardous waste incineration]	kg	$7.15x10^{-7}$	$1.35x10^{-7}$	$3.61x10^{-6}$
CH: disposal, emulsion paint remains, 0% water, to hazardous waste incineration [hazardous waste incineration]	kg	$3.15x10^{-6}$	$5.94x10^{-7}$	$1.59x10^{-5}$
CH: disposal, municipal solid waste, 22.9% water, to sanitary landfill [sanitary landfill facility]	kg	$2.34x10^{-4}$	$4.40x10^{-5}$	$1.18x10^{-3}$
CH: disposal, used mineral oil, 10% water, to hazardous waste incineration [hazardous waste incineration]	kg	$2.62x10^{-4}$	$4.94x10^{-5}$	$1.32x10^{-3}$
CH: disposal, wood untreated, 20% water, to municipal incineration [municipal incineration]	kg	$5.09x10^{-5}$	$9.58x10^{-6}$	$2.57x10^{-4}$
CH: methanol, at regional storage [organics]	kg	$2.94x10^{-4}$	$5.54x10^{-5}$	$1.49x10^{-3}$
DE: disposal, hazardous waste, 0% water, to underground deposit [underground deposit]	kg	$3.16\ x10^{-4}$	$5.945x10^{-5}$	$1.60\ x10^{-3}$
GB: electricity, medium voltage, at grid [supply mix]	MJ	0.352	0.0663	1.78
GLO: chemicals inorganic, at plant [inorganics]	kg	$1.12x10^{-5}$	$2.12\ x10^{-6}$	$5.70\ x10^{-5}$
GLO: chemicals organic, at plant [organics]	kg	$8.51x10^{-6}$	$1.60\ x10^{-6}$	$4.30\ x10^{-5}$
GLO: diesel, burned in diesel-electric generating set [fuels]	MJ	0.0670	0.0126	0.339
GLO: plant onshore, natural gas, production [Appropriation]	pcs.	$5.59\ x10^{-9}$	$1.05x10^{-9}$	$2.82\ x10^{-8}$
GLO: well for exploration and production, onshore [Appropriation]	m	$4.15\ x10^{-5}$	$2.57\ x10^{-6}$	$6.17\ x10^{-4}$
NO: sweet gas, burned in gas turbine, production [power plants]	m^3	0.0377	0.00710	0.190
RER: ethylene glycol, at plant [organics]	kg	$1.82\ x10^{-4}$	$3.43x10^{-5}$	$9.21\ x10^{-4}$

Table B14: (Continued)

Ecoinvent data	Units	Average	Minimum	Maximum
RER: tap water, at user [Appropriation]	kg	0.0123	0.00232	0.0622
RER: transport, freight, rail [Railway]	t.km	$3.55x10^{-5}$	$6.70\ x10^{-6}$	$1.79\ x10^{-4}$
RER: transport, lorry >16t, fleet average [Street]	t.km	$4.92x10^{-5}$	$9.27\ x10^{-6}$	$2.49\ x10^{-4}$
Natural gas Ecoinvent [Natural gas (resource)]	m^3	1.00	1.00	1.00
Water (river water) [Water]	Kg	0.0123	0.00232	0.0622
Water (sea water) [Water]	Kg	0.0123	0.00232	0.0622
Water, salt, sole [Water]	m^3	$1.23x10^{-5}$	$2.32\ x10^{-6}$	$6.22\ x10^{-5}$

BVI. Land use change

The four cases consider impacts to agricultural land. Annual cropland refers to agricultural land which is harvested once a year while perennial cropland is land which is harvested multiple times per year. The impact to greenhouse gas (GHG) emissions is calculated by calculating the emissions from land transformation for the four land types (BSI, 2011):

$$GHG\ emissions = \sum A \times EF \qquad (\text{t } CO_{2\text{-Eq.}}/\text{year}) \qquad (B5)$$

where:

A area of land transformed (ha)

EF emission factor for type of land transformed (t $CO_{2\text{-Eq.}}$/ha-year).

The area of a pad (one vertical well) is assumed to be 3 ha and each pad contains 4 (horizontal) wells (AMEC, 2013; Lewis et al., 2014). The lifespan of the well, as mentioned in Chapter 3, is 30 years. These were used to calculate the emissions from land use change. The emissions from land use change are then divided by the EUR of the well (using the minimum, average and maximum EUR) to calculate emissions per m^3 gas produced. This is then converted into emissions per kWh electricity generated by multiplying by the LHV (11.3 kWh/m^3) and factoring in the efficiency of the CCGT power plant (53%).

Nomenclature

A	area of land transformed (ha)
b	Arps' decline exponent (-)
c_1	capacity of well 1
c_2	capacity of well 2
C_1	amount of materials and energy used in well 1
C_2	amount of materials and energy used in well 2
Ch	annular capacity of the well
D	wellbore diameter (m)
Di	initial decline constant ($month^{-1}$)
EF	emission factor for type of land transformed (t $CO_{2\text{-Eq.}}$/ha-year)
L	length drilled (m)
P	porosity of cuttings (-)
q_i	initial production rate (m^3/month)
$q(t)$	monthly production rate (m^3/month)
SG	specific gravity of the cuttings (kg/m^3)
t	month t (month)
W_{cg}	solid (drill cuttings) drilling waste

References

AMEC. **2013**. *Strategic environmental assessment for further onshore oil and gas licensing*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/consultations/environmental-report-for-further-onshore-oil-and-gas-licensing.

BSI. **2011**. *PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of good and services*. *British standards Institution (BSI)*. London, UK. Retrieved from: http://shop.bsigroup.com/upload/shop/download/pas/pas2050.pdf.

Clark, C., Burnham, A., Harto, C. and Horner, R. **2013**. *Hydraulic fracturing and shale gas production: Technology, impacts, and regulations*. *Argonne National Laboratory*. Oak Ridge, TN, USA. Retrieved from: http://www.afdc.energy.gov/uploads/publication/anl_hydraulic_fracturing.pdf.

George, D. L. and Bowles., E. B. J. **2011**. Shale gas measurement and associated issues. *Pipeline and Gas Journal*, 238.

Lapeyrouse, N. J. **2002**. *Formulas and calculations for drilling, production, and workover: All the formulas you need to solve drilling and production problems*, Second, Burlington, MA, USA: Gulf Professional Publishing.

Lewis, C., Speirs, J. and MacSweeney, R. **2014**. *Getting ready for UK shale gas: Supply chain and skills requirements and opportunities*. *United Kingdon Onshore Oil and Gas and Ernst and Young*. London, UK. Retrieved from: http://www.ey.com/Publication/vwLUAssets/Getting_ready_for_UK_shale_gas/$FILE/EY-Getting-ready-for-UK-shale-gas-April-2014.pdf.

Russell, C. and Hargreaves, T. R. **2013**. *Permit application: Irlam wells waste management plan*. *IGas Energy Plc*. Manchester, UK. Retrieved from: https://www.whatdotheyknow.com/request/205082/response/511630/attach/6/IRLM%20EPA%20008.pdf.

SONRIS. **2013**. *Well Information.* Strategic Online Natural Resources Information System (SONRIS): Baton Rouge, LA, USA (March 2014) Retrieved from: http://sonlite.dnr.state.la.us/sundown/cart_prod/cart_con_wellinfo1.

Symmons, D., Rushing, J. A. and Blasingame., T. A. **2010**. *Hybrid Rate-Decline Models for the Analysis of Production Performance in Unconventional Reservoirs (Conference)*. SPE Annual Technical Conference and Exhibition. 19-22 September 2010 Florence, IT.

Towler, G. and Sinnot, R. **2008**. *Chemical engineering design: Principles, practice and economics of plant and process design*, London, UK: Elsevier.

Appendix C

CI. Capital costs of a shale gas well

Table C1: Capital cost of a shale gas well (Amion, 2014; Cronin, 2013; Lewis et al., 2014; Taylor and Lewis, 2013).

Activity	**Cost per well (M£)**
Seismic testing	0.02
Pre-licensing and enabling	0.01
Exploration and appraisal	1.50
Hydraulic fracturing	5.14
Equipment	4.27
Proppant	0.51
Chemicals	0.19
Mobilisation/demobilisation	0.11
Miscellaneous	0.06
Drilling and completion	2.07
Steel casing	0.58
Rig hire	0.54
Ancillary equipment and services	0.30
Cementing	0.21
Directional drilling	0.19
Drilling fluid	0.14
Drill rig fuel	0.12
Storage and transportation	0.32
Waste transportation	0.19
Water storage	0.03
Water transportation	0.10
Waste disposal	0.69
Water management	0.36
Drilling waste	0.33
Decommissioning	0.28
Community charter (initial lump-sum payment)[a]	2.5×10^{-3}
Additional costs	0.13
Pad preparation, construction and security	0.01
Gathering and gas processing	0.04-0.05
Other	0.07-0.08
Total	**10.16**

[a] The annual payments are not included as they depend on the annual production of shale gas and are therefore a variable cost.

CII. Sand and chemical quantities

Table C2: Quantity of sand and chemicals required for hydraulic fracturing in the UK (Bide et al., 2014; Cuadrilla, 2013; Lewis et al., 2014).

	Sand		Chemicals	
Number of wells	*Quantity (t)*	*Cost (M£)*	*Quantity (kg)*	*Cost (M£)*
One horizontal well	2,250	0.507	88	0.187
Four horizontal wells	9,000	2	350	0.748
Well pad with 10 wells	90,000	20	3,500	7.48
Peak production (400 wells fractured annually)	900,000	200	35,000	74.8

CIII. Break-even price at different discount rates

Table C3: Estimated break-even prices of shale gas for different discount rates and estimated ultimate recovery (EUR) values.

Price (pence/kWh)	Discount rate				
	5%	*10%*	*15%*	*20%*	*30%*
Low EUR	25.67	31.79	37.78	43.69	55.47
Average EUR	2.13	2.63	3.13	3.62	4.60
High EUR	0.21	0.26	0.31	0.35	0.45

CIV. Electricity costs

Table C4: Life cycle (levelised) costs for 2030 electricity for different electricity and shale gas scenarios.

	Costs for different electricity scenarios (pence/kWh)		
Shale gas scenario	*Best*	*Central*	*Worst*
Low shale penetration			
Low EUR	10.92	10.90	10.48
Average EUR	9.40	9.40	9.46
High EUR	8.69	8.71	8.82
High shale penetration			
Low EUR	14.56	14.48	14.15
Average EUR	9.48	9.48	9.54
High EUR	8.52	8.54	8.67

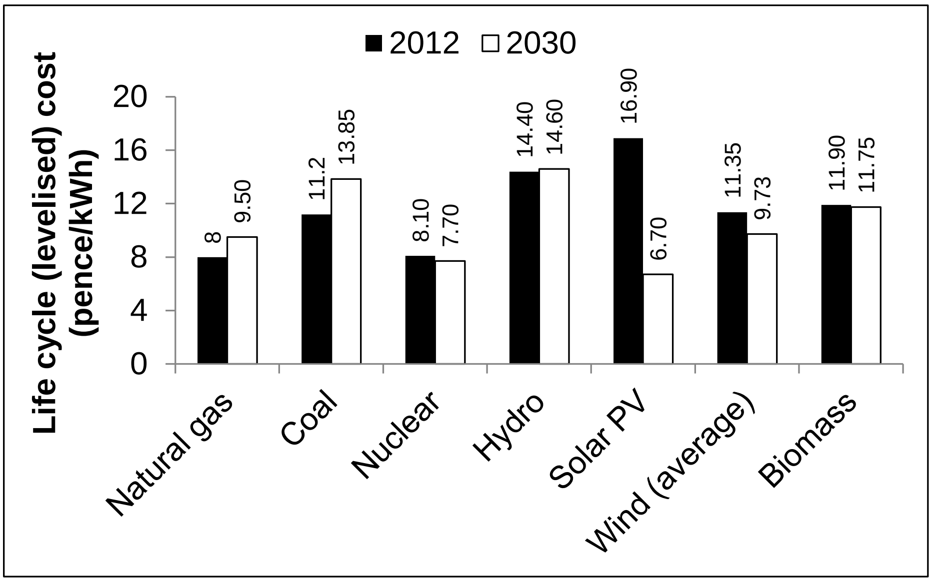


Figure C1: Comparison of 2012 and 2030 life cycle (levelised) costs of different electricity options in the UK [2012 costs: DECC (2012; 2013). 2030 costs: (DECC, 2013)]

[“Wind average” represents the average costs of offshore and onshore installations. <u>2030 Capital costs</u>: natural gas: 0.90 pence/kWh; coal: 4.60 pence/kWh; nuclear: 7.00 pence/kWh; hydro: 11.29 pence/kWh; solar PV: 5.70 pence/kWh; wind: 7.70 pence/kWh; biomass: 4.50 pence/kWh. <u>2030 Fuel costs</u>: natural gas: 4.90 pence/kWh; coal: 3.60 pence/kWh; nuclear: 0.50 pence/kWh; hydro: 0.00 pence/kWh; solar PV: 0.00 pence/kWh; wind: 0.00 pence/kWh; biomass: 5.30 pence/kWh. <u>2030 O&M costs</u>: natural gas: 0.40 pence/kWh; coal: 0.50 pence/kWh; nuclear: 0.20 pence/kWh; hydro: 3.31 pence/kWh; solar PV: 1.00 pence/kWh; wind: 2.03 pence/kWh; biomass: 1.95 pence/kWh. <u>2030 CO_2 costs</u>: natural gas: 3.30 pence/kWh; coal: 5.15 pence/kWh; nuclear: 0.00 pence/kWh; hydro: 0.00 pence/kWh; solar PV: 0.00 pence/kWh; wind: 0.00 pence/kWh; biomass: 0.00 pence/kWh.]

References

Amion. **2014**. *Potenital economic impacts of shale gas in the Ocean Gateway*. *IGas Energy plc and Peel Environment Ltd*. Liverpool, UK. Retrieved from: http://www.igasplc.com/media/10851/ocean-gateway-shale-gas-impact-study.pdf.

Bide, T., Brown, T. J., Hobbs, S. F. and Idoine, N. **2014**. *United Kingdom minerals year 2013*. *British Geological Survey*. London. Retrieved from.

Cronin, K. **2013**. *Community engagement charter oil and gas from unconventional reservoirs*. *United Kingdon Onshore Oil and Gas (UKOOG)*. London, UK. Retrieved from: http://www.ukoog.org.uk/community/charter.

Cuadrilla. **2013**. *Fracturing Fluid* [Online]. Available: http://www.cuadrillaresources.com/what-we-do/hydraulic-fracturing/fracturing-fluid/ [Accessed 2014].

DECC. **2013**. *Electricity generation costs*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/publications/electricity-generation-costs-december-2013.

Lewis, C., Speirs, J. and MacSweeney, R. **2014**. *Getting ready for UK shale gas: Supply chain and skills requirements and opportunities*. *United Kingdon Onshore Oil and Gas and Ernst and Young*. London, UK. Retrieved from: http://www.ey.com/Publication/vwLUAssets/Getting_ready_for_UK_shale_gas/$FILE/EY-Getting-ready-for-UK-shale-gas-April-2014.pdf.

Taylor, C. and Lewis, D. **2013**. *Getting shale gas working*. *Institute of Directors (IoD)*. London, UK. Retrieved from: www.iod.com/~/media/.../IoD_Getting_shale_gas_working_MAIN_REPORT.pdf.

Appendix D

DI. Electricity technologies

Table D1 shows electricity technology specifications for which direct employment (equation (13) in Chapter 5) and worker injuries (equation (16) in Chapter 5) have been estimated. For the remaining technologies, the values for these two indicators have been sourced from Stamford and Azapagic (2012) .

Table D1: Specification of shale gas, LNG and hydroelectricity (Mishra and Singh, 2015; Statkraft, 2017; BEIS, 2016; Mott MacDonald, 2010; Parsons Brinckerhoff, 2013).

Specification	Shale gas	LNG	Hydro
Plant type	CCGT[a]	CCGT[a]	Reservoir
Lifetime (yr)	25	25	30
Electricity generation over lifetime (TWh)	183	183	2.6

[a] CCGT: combined cycle gas turbine.

DII. Employment

DII.I. Direct employment

The data used to estimate the direct employment for shale gas, LNG and hydroelectricity (equation (13) in Chapter 5) are given in Table D2. As mentioned in the previous section, the employment values for the other technologies have been sourced from Stamford and Azapagic (2012). During the extraction of shale gas, 194 jobs are created per well pad, 40 in pre-development, 134 in pad preparations and 20 in gas production (AMEC, 2013; Lewis et al., 2014). To sustain a power plant over its lifespan, this work estimates that 6.2 shale gas well pad (248 wells) would be needed, based on data from chapters 3 and 4.

Table D2: Data and assumptions for the estimation of direct employment (AMEC, 2013; Lewis et al., 2014; Statkraft, 2017).

	Number of jobs[a], persons (duration, yrs)		
Life cycle stage	*Shale gas*	*LNG*	*Hydro*
Fuel extraction	1,203 (1-30)[b]	-	-
Fuel transportation	6 (25)	4,054 (0.1)[c]	-
Power plant construction	800 (3)	800 (3)	400 (3)
Power plant operation	50 (25)	50 (25)	26 (30)
Power plant decommissioning	200 (0.5)	200 (0.5)	-[e]
Liquefaction[d]	-	160 (30)	-
Regasification[d]	-	79 (30)	-
Overhauls	200 (0.2)	200 (0.2)	30 (0.5)

[a] Total number of jobs needed to bring sufficient number of shale gas wells into operation to a produce enough gas to sustain a power plant over its operating life. Number of jobs in LNG fuel extraction was assumed to be the same as UK offshore gas extraction and was sourced from Stamford and Azapagic (2012).
[b] Pad pre-development and preparation take up to a year and the producing lifespan of the well is 30 years.
[c] The shipment of LNG from Qatar to the UK takes two weeks and an LNG carrier has a crew of 30 (Maritime Connector, 2017; South Hook LNG Terminal, 2017). 135 LNG shipments are needed to provide a power plant with enough fuel to sustain it over its lifespan (Qatargas, 2017).
[d] LNG only.
[e] Decommissioning not considered as hydroelectricity plants are typically refurbished instead of decommissioned (BHA, 2017).

DII.II. Local employment

The data used to estimated local employment related to shale gas, as defined by equation (14) in Chapter 5, are summarised in Table D3.

Table D3: Data and assumptions for the estimation of local employment in the life cycle of shale gas.

Life cycle stage	**Number of local employees**	**Total number of employees needed**	**Source**
Well pad pre-development	241	241	Lewis et al. (2014); Rigzone (2014)
Pad preparation	582	831	Lewis et al. (2014); Rigzone (2014)
Gas production and processing	73	124	Lewis et al. (2014); Rigzone (2014)
Gas distribution	6	6	Lewis et al. (2014); Rigzone (2014)
Power plant operation	50	50	Cooper (2015); EDF Energy (2017)
Power plant construction	800	800	Cooper (2015); Hendry (2011)
Power plant decommissioning	200	200	Hendry (2011)

DII.III. Gender equality

Table D4 provides the percentage of male and female workers in the oil and gas industry in the UK, which has been used to estimate the gender equality index according to equation (15) in Chapter 5. For comparison, the data for some other countries are also shown.

Table D4: Percentage of male and female workforce in the oil and gas industry in the UK and some other countries (Czebiniak, 2014; McGrath and Marinelli, 2012; Oil & Gas UK, 2011).

Country	**Female workforce (%)**	**Male workforce (%)**
UK	3.7	96.3
Norway	19.0	81.0
Australia	12.0	88.0
Canada	21.0	79.0
USA	15.0	85.0

DIII. Health and safety: worker injuries

The data used to estimated worker injuries related to shale gas, LNG and hydroelectricity (equation (16) in Chapter 5), are summarised in Table D5; they refer to the year 2014/2015. Injuries included in the estimate are fatalities, major injuries and less serious injuries that cause an absence from work of more than three days. The injury rates for the other technologies have been sourced from Stamford and Azapagic (2012) based on the same definition of injuries as above.

Table D5: Data and assumptions for the estimation of worker injuries by life cycle stage (HSE, 2014; HSE, 2017; Ministry of Public Health (State of Qatar), 2017).

	Injury rate (injuries/1,000 workers)		
Life cycle stage	*Shale gas*	*LNG*[a]	*Hydro*
Well pad pre-development	4.50	15.66	-
Pad preparation	4.50	15.66	-
Gas production and processing	4.50	15.66	-
Gas distribution	1.86	4.57	-
Liquefaction[b]	-	4.57	-
Regasification[b]	-	4.57	-
Power plant operation	1.86	1.86	1.86
Power plant construction	29.42	29.42	29.42
Power plant decommissioning	29.42	29.42	29.42

[a] LNG considered only the liquefaction, transport and gasification.
[b] LNG only.

DIV. Nuisance: traffic increase

The literature data suggest that between 2-659 truck trips would be needed during the different pre-development stages of shale gas (Broderick et al., 2011). On average, this translates to 0.36-14 truck trips per day to bring a well into operation. The data for the estimation of the congestion reference flow, according to equation (17) in Chapter 5, can be found in tables D6 and D7. The values in the tables for low and high vehicle capacity represent the range in vehicle capacity (CAP in equation (17)) for the different road types and include the increases in traffic expected for shale gas development.

DV. Public perception

DV.I. Public support

The data used for the calculation of the public support index have been collected from numerous surveys and their results averaged to calculate the values listed in Table D8. This approach has been taken because the level of support/opposition for shale gas and other electricity options differed significantly across the surveys. This variation is illustrated for shale gas in Figure D1. Differences in the results can be attributed to various factors, such as the framing of questions, sample sizes, timing of survey and geographical location of people surveyed.

Table D6: Data for the calculation of the public support index (ComRes, 2015; Cunningham, 2014; DECC, 2015; Spence et al., 2010; Wire and staff reports, 2008).

Technology	Support (%)	Oppose (%)	Unsure (%)
Shale gas	37	32	31
Conventional gas	65	22	22
LNG	42	27	31
Coal	36	43	22
Hydro	76	4	20
Nuclear	76	4	20
Solar PV	81	6	14
Offshore wind	73	8	19
Biomass	63	6	30

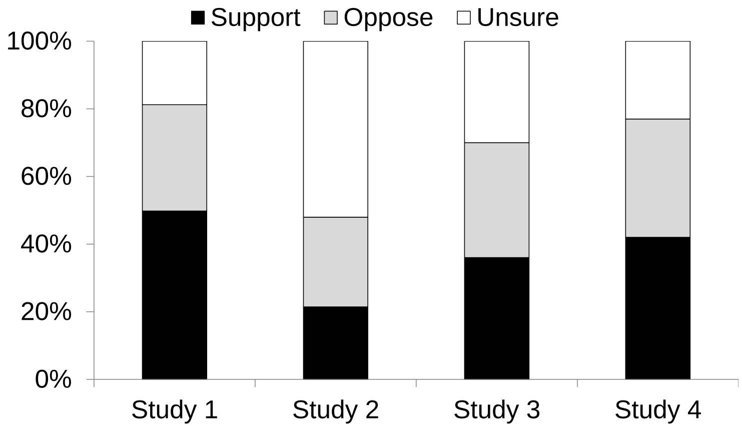


Figure D1: Comparison of public attitudes towards shale gas in the UK in different studies.

[Study 1: O'Hara et al. (2015); Study 2: DECC (2015); Study 3: Castell et al. (2014); Study 4: ComRes (2015).]

Table D7: Data for estimation of the congestion reference flow for rural roads (Standards for Highways, 1997).

Parameter in equation. (17)	**Road type**						
	Single lane	*Wide single lane*	*Dual 2 lane (all purpose)*	*Dual 3 lane (all purpose)*	*Dual 2 lane (motorway)*	*Dual 3 lane (motorway)*	*Dual 4 lane (motorway)*
Low vehicle capacity per road lane, *CAP* (vehicles/day)	1,153	1,153	1,797	1,797	1,921	1,921	1,921
High vehicle capacity per road lane, *CAP* (vehicles/day)	1,113	1,113	1,744	1,744	1,855	1,855	1,855
Number of lanes on the road, *L* (-)	1	1	2	3	2	3	4
Width factor, W_f (-)	1	1.46	1	1	1	1	1
Proportion of daily traffic flow during peak hours, *PkF* (-)	9.6	9.6	9.4	9.4	10	10	10
The directional split of flow during peak hours, *PkD* (-)	58.4	58.4	57.4	57.4	56.3	56.3	56.3
AADT/AAWT[a] (-)	0.98	0.98	0.97	0.97	0.93	0.93	0.93

[a] Ratio of annual average daily and weekday flows, respectively.

Table D8: Data for estimation of the congestion reference flow for urban roads (Standards for Highways, 1999).

Parameter in equation. (17)	Road type							
	Urban motorway	*UAP[a] 1 (SC[b])*	*UAP 1 (DC[b])*	*UAP 2 (SC)*	*UAP 2 (DC)*	*UAP 3 (SC)*	*UAP 3 (DC)*	*UAP 4 (SC)*
Low vehicle capacity per road lane, *CAP* (vehicles/day)	3,800-6,800	530-3,200	3,150-4,900	530-2,600	2,750-4,500	450-1,520	2,100-2,400	350-1,310
High vehicle capacity per road lane, *CAP* (vehicles/day)	4,000-7,200	680-3,300	3,350-5,200	680-2,700	2,950-4,800	600-1,620	2,300-3,300	500-1,410
Number of lanes on the road, *L* (-)	2	1	2	1	2	1	2	1
Width factor, W_f (-)	1	1	1.46	1	1.46	1	1.46	1
Proportion of daily traffic flow during peak hours, *PkF* (-)	10	9.6	9.4	9.6	9.4	9.6	9.4	9.6
The directional split of flow during peak hours, *PkD* (-)	56.3	58.4	57.4	58.4	57.4	58.4	57.4	58.4
AADT/AAWT[c] (-)	0.93	0.98	0.97	0.98	0.97	0.98	0.97	0.98

[a] UAP: urban all-purpose.
[b] SC: single-lane carriageway; DC: dual carriageway. Data not available for UAP 4 (DC).
[c] Ratio of annual average daily and weekday flows, respectively.

DV.II. Media impact

The data used to determine the media impact according to equations (18)-(21) in Chapter 5 are presented in Table D9.

Table D9: The social media metrics used to calculate the social media impact of different stakeholders[a].

	NGOs		***Operators***			***Government bodies and academia***		
	Greenpeace	*Friends of the Earth*	*Cuadrilla Resources*	*iGas*	*Third Energy*	*Department of Energy and Climate Change*	*Environment Agency*	*University of Manchester*
Twitter followers	1,470,000	143,000	1,902	647	43	83,500	352,000	14,400
Twitter tweets	31,100	20,000	234	194	0	7,015	18,700	2,352
Facebook likes	2,328,529	103,348	No profile	No profile	No profile	No profile	19,729	98,092
LinkedIn followers	93,563	5,969	323	1,227	No profile	16,395	42,418	No profile
LinkedIn employees	1,001-5,000	51-200	11-50	51-200	No profile	1,001-5,000	10,001+	No profile
Google+ followers	61,404	390	7	4	No profile	21	411	22,344
Google+ views	7,208,278	169,984	7,035	5,256	No profile	459,320	6,240	25,807,349
YouTube subscribers	102,169	7,737	74	0	No profile	827	1,367	65,655
YouTube videos	500+	100+	25	2	No profile	77	100+	100+
YouTube Views	50,550,940	9,505,673	21,827	3,190	No profile	656,366	591,980	1,358,677

[a] As of 13.00 on 20 October 2015.

DVI. Local communities

DVI.I. Spending on local suppliers

The data used to determine the spending on local suppliers, estimated according to equation (22) in Chapter 5, are presented in Table D10. The potential spending has been determined based on whether there is already an industry in the UK for the equipment and services needed. As shown in the table, the potential percentage spending is 100% for all equipment and services except for: specialised hydraulic fracturing equipment, drilling rigs and directional drilling. As hydraulic fracturing is not currently an activity being carried out onshore in the UK, it is more than likely that this equipment will have to be imported from overseas; mostly likely the USA. There are a small number of onshore oil and gas wells in the UK, but up to 400 wells could be drilled per year which would require 50 landward and workover rigs (House of Lords, 2014; Lewis et al., 2014). Also, directional drilling at the depths of thousands of meters below the surface is not an activity being carried in the UK – it is used for telecommunication cables and water pipelines which are at much shallower depths.

Table D10: Estimated costs of for bringing 4000 shale gas wells into operation in the UK.

Category	**Total spending (M£)**[a]	**Potential spending on local suppliers**	
		(%)	*(M£)*
Specialised hydraulic fracturing equipment	17,000	0	0
Sand	2,000	100	2,000
Chemicals	748	100	748
Steel casing	2,300	100	2,300
Drilling rigs	2,200	0-100	0-2,200
Ancillary and services	1,200	100	1,200
Cement	819	100	819
Directional drilling	747	0-100	0-747
Drilling fluid	571	100	571
Drill rig fuel	457	100	457
Wastewater treatment and management	1,500	100	1,500
Drilling waste management	1,300	100	1,300
Water transport and storage	523	100	523
Waste transport and storage	754	100	754
Total	***32,119***		***12,172-15,119***

[a] Over 15 years, time required for UK shale gas industry to reach maturity (Lewis et al., 2014).

DVI.II. Direct community investment

The data used to estimate the direct community investment, based on to equation (23) in Chapter 5, are presented in Table D11.

Table D11: Data used for the estimation of direct community investment (National Grid, 2017; npower, 2017).

Operator	Annual community investment (M£/yr)	Annual revenue (M£/yr)[a]	Operating lifespan (years)[b]
Shale gas	0.47-0.89	47-89	30
Gas distribution	0	15,115	-
Power plant	4.10-10	399-582	25

[a] The revenue for the shale gas (estimated in Chapter 3) and power plant operator is for one well site and one power plant, respectively, while the revenue for the gas distribution operator is for the entire UK gas transmission system (National Grid). In reality, a shale gas or power plant operator will operate multiple well sites/power plants.
[b] The UK gas transmission system is in continuous operation and remains in operation while the UK uses natural gas as a fuel/energy source.

DVII. Infrastructure and resources

DVII.I. Diversity of fuel supply

The gas and electricity mixes used to calculate the diversity of fuel supply according to equation (24) in Chapter 5 are given in tables D12 and D13, respectively. The supply mix of the fuels for other electricity options is given in Table D14. Both the present (2012) and possible future (2030) situations are considered. The fuel mix of coal, oil, uranium, biomass and electricity imports are assumed to be same in 2030 as in 2012 due to a lack of data on future fuel mixes. Around 33 TWh of carbon capture and storage for coal and gas electricity is anticipated in 2030 (DECC, 2013c) which has been split equally between coal and gas to calculate the diversity of fuel supply score of the 2030 electricity mix scenarios.

Table D12: UK gas mix in 2012 (DECC, 2013c) and 2030 scenarios (adapted from Williams et al. (2011)).

Gas source	2012 (bn m^3)	2030 (low shale gas penetration) (bn m^3)	2030 (high shale gas penetration) (bn m^3)
UK north sea	42	16	16
UK shale gas	0	4	25
Pipeline imports-Norway	27	33	33
Pipeline imports-Netherland	7	10	10
Pipeline imports-Belgium	1	0	0
LNG imports-Qatar	14	25	4
Total	91	88	88

Table D13: UK electricity mix in 2012 and 2030 (DECC, 2013b; DECC, 2013c).

Electricity source	2012 (TWh)	2030 (TWh)
Coal	135.9	18.5[a]
Oil	2.7	3.6
Natural gas	98.2	101.2[a]
Nuclear	63.9	101.9
Wave, wind and solar	20.8	113.0
Other[b]	32.4	46.9
Total	353.9	385.1

[a] Includes 16.7 TWh coal and gas CCS.
[b] Hydroelectricity, biomass, fuel oil and electricity imports.

Table D14: Origin of other fuels used to generate electricity in the UK (DECC, 2013a). Table lists domestic use and imports.

Coal	**Oil**	**Nuclear (uranium)**	**Biomass (woodchips)**	**Electricity imports**
UK (21.88%)	UK (17.72%)	Kazakhstan (26.72%)	UK (5.80%)	France (66.37%)
Russia (33.06%)	Algeria (12.81%)	Russia (17.96%)	EU (20.56%)	Netherlands (33.63%)
USA (20.56%)	Angola (1.07%)	Niger (14.72%)	Canada (19.81%)	
Colombia (18.11%)	Brazil (0.37%)	Australia (13.52%)	Egypt (0.02%)	
Australia (2.34%)	Cameroon (0.06%)	Canada (12.58%)	Indonesia (0.02%)	
EU (1.43%)	Canada (1.88%)	US (3.97%)	Malaysia (0.02%)	
Canada (0.81%)	Congo (0.28%)	EU (2.69%)	Russia (0.39%)	
South Africa (0.25%)	Denmark (3.47%)	Uzbekistan (2.47%)	Ukraine (0.02%)	
Other (1.55%)	Egypt (0.91%))	Namibia (2.20%)	USA (53.36%)	
	Equitorial Guinea (2.44%)	Other (2.03%)		
	France (0.05%)	Malawi (0.85%)		
	Hong Kong (0.15%)	Ukraine (0.16%)		
	Libya (0.84%)	South Africa (0.14%)		
	Netherlands (0.08%)			
	Nigeria (9.90%)			
	Norway (37.94%)			
	Other Africa (2.52%)			
	Other Europe (0.13%)			
	Papua New Guinea (0.40%)			
	Russia (2.46%)			
	Saudi Arabia (2.99%)			
	Tunisia (0.33%)			
	Venezuela (0.87%)			
	Other (0.33%)			

DVII.II. Wastewater treatment

Hydraulic fracturing requires large volumes of water (Table D15), of which 10-300% returns to the surface as flowback fluid (wastewater), resulting in large quantities of wastewater being produced. However, the total volume produced is spread out throughout the well's lifespan. In the first two to four weeks after well completion, around 10-40% of the injected fluid (871-10,000 m^3) returns to the surface (Clark et al., 2013; Lutz et al., 2013). Any remaining fluid which returns to the surface will do so later on. The number of trips required in the first month is expected to be the maximum, as the rate at which water returns to the surface after the initial period is much lower. Planning transport based on predicted volumes during set periods of the well's life can help in managing transporting and on-site storage for wastewater.

In the UK, wastewater plants are owned and operated by utility companies. Within and close to the UK's Bowland-Hodder shale play catchment area, there are five companies: United Utilities, Yorkshire Water, Severn Trent Water, Anglian Water and Dwy Cymru (Welsh Water) (Andrews, 2013; Google Earth, 2015; UK water projects online, 2015). However, when the location of the wastewater plants is taken into consideration, the number of utility companies with treatment plants within the catchment area reduces to four. The majority of plants are small facilities, only capable of treating domestic wastewater. These would be unsuitable for hydraulic fracturing wastewater as it has a high concentration of dissolved solids and contains other chemicals not found in domestic wastewater. These include barium, strontium, arsenic, selenium and volatile organic compounds (Fontenot et al., 2013; Oram et al., 2011; Orem et al., 2014). For a detailed review of wastewater composition and constituents, see Section 3.2.2 and 3.2.3 in Chapter 2. The wastewater treatment plants listed in Table D16 are those which have been identified as capable of treating trade effluent. Their treatment capacity and maximum flow (to full treatment) have been used to calculate how long it would take each facility to treat the total amount of wastewater produced by a well over its lifespan.

Table D15: Flowback fluid volume ranges[a] (Clark et al., 2013; Freyman and Salmon, 2013).

Flowback (%)	**Low hydraulic fracturing volume (8,706 m^3)**	**High hydraulic fracturing volume (25,000 m^3)**
10	871	2,500
20	1,741	5,000
30	2,612	7,500
40	3,482	10,000
50	4,353	12,500
60	5,224	15,000
70	6,094	17,500
75	6,530	18,750
100	8,706	25,000
150	13,059	37,500
200	17,412	50,000
300	26,118	75,000

[a] For context, an Olympic-size swimming pool has the volume of 2,500 m^3.

Table D16: Wastewater treatment works data (UK water projects online, 2015).

Wastewater treatment plant	**Treatment capacity (m^3/day)**	**Flow to full treatment (m^3/s)**	**Time to treat wastewater (hours)**
Bromborough	33,367	0.71	0.34-29.55
Davyhulme	385,000	9.09	0.03-2.29
Liverpool	256,667	11.00	0.02-1.89
Wigan	89,833	1.93	0.13-10.78
Blackburn Meadows	205,333	1.83	0.13-11.39
Denaby, Mexborough and Burcroft combined	8,983	0.21	1.13-97.35
Huddersfield	37,987	1.37	0.18-15.18
Knostrop	256,667	5.28	0.05-3.95
Clay Mills	108,282	1.30	0.19-15.98
Derby	128,333	2.38	0.10-8.74
Stoke Bardolph	166,833	1.97	0.12-10.59
Strongford	89,833	2.74	0.09-7.61
Wanlip	231,000	3.59	0.07-5.81
Chester	32,360	0.92	0.26-22.60
Five Fords	24,640	0.81	0.30-25.85

DVII.III. Land use

The sites of special interest are listed in Table D17. Only sites situated in counties which overlap with the Bowland-Hodder shale play are considered.

Table D17: Sites of special interest in counties in the Bowland-Hodder shale play.

		National Parks			
Peak District	Lake District	Yorkshire Dale	North York Moors		
		Special Areas of Conservation (SAC)			
Dee Estuary	Humber Estuary	North Pennine Dales Meadows	North Pennine Moors	Morecambe Bay	Morecambe Bay Pavements
Llwyn	Elwy Valley Woods	Berwyn and South Clwyd Mountains	Tanat and Vyrnwy Bat Sites	Alyn Valley Woods	Bee`s Nest and Green Clay Pits
Gang Mine	River Mease	Peak District Dales	Thorne Moor	Flamborough Head	Lower Derwent Valley
River Derwent	Calf Hill and Cragg Woods	Baston Fen	Grimsthorpe	Saltfleetby–Theddlethorpe Dunes and Gibraltar Point	The Wash and North Norfolk Coast
North Shotts Moss	West Fannyside Moss	Clyde Valley Woods	Arnecliff and Park Hole Woods	Beast Cliff – Whitby (Robin Hood`s Bay)	Craven Limestone Complex
Eller`s Wood and Sand Dale	Fen Bog	Ingleborough Complex	Kirk Deighton	Ox Close	Skipwith Common
North York Moors	Brown Moss	The Stiperstones and The Hollies	Fenn`s, Whixall, Bettisfield, Wem and Cadney Mosses	Braehead Moss	Coalburn Moss
Cranley Moss	Red Moss Waukenwae Moss	Cannock Chase	Mottey Meadows	Pasturefields Salt Marsh	Cannock Extension Canal
Rixton Clay Pits	Manchester Mosses	Strensall Common			
		Special Protected Areas (SPA)			
Mersey narrows and north Wirral Foreshore	South Pennine Moors	Ribble and Alt estuaries	Dutton Estuary	Morecambe Bay	Leighton Miss
Bowland Fells	North Norfolk Coast	Gibraltar Point	Thorne and Hatfield Moors	Lower Derwent Valley	Hornsea Mere
Humber Flats, marshes and coast	North York Moors	Flamborough head and Bempton cliffs	North Pennine Moors	Teesmouth and Cleveland Coast	
		Area of Outstanding Natural Beauty (AONB)			
Forest of Bowland	Nidderdale				

Table D17: (Continued)

UNESCO World Heritage sites					
Liverpool-Maritime Mercantile City	Saltaire				
Natura200 and Ramsar (included in SAC and SPA)					
Abbotts Hall Farm	East Dartmoor Woods & Heaths NNR	Fenn’s, Whixall & Bettisfield Mosses NNR	Geltsdale RSPB Nature Reserve	Ingleborough NNR : Limestone Country Project (LIFE)	New Forest (LIFE)
Ravine WoodLIFE (LIFE)	Saltfleetby-Theddlethorpe Dunes NNR	Sunart Oakwoods Initiative (SOI)	Wash NNR, The	Abberton Reservoir	Alde-Ore Estuary
Arun Valley	Avon Valley	Benfleet and Southend Marshes	Blackwater Estuary (Mid-Essex Coast Phase 4)	Breydon Water	Broadland
Chesil Beach and The Fleet	Chichester and Langstone Harbours	Chippenham Fen	Colne Estuary (Mid-Essex Coast Phase 2)	Crouch and Roach Estuaries (Mid-Essex Coast Phase 3)	Deben Estuary
Dengie (Mid-Essex Coast Phase 1)	Dersingham Bog	Dorset Heathlands	Duddon Estuary	Dungeness to Pett Level	Esthwaite Water
Exe Estuary	Foulness (Mid-Essex Coast Phase 5)	Gibraltar Point	Hamford Water	Holburn Lake and Moss	Humber Estuary
Irthinghead Mires	Isles of Scilly	Lee Valley	Leighton Moss	Lindisfarne	Lower Derwent Valley
Malham Tarn	Martin Mere	Medway Estuary and Marshes	Mersey Estuary	Mersey Narrows and North Wirral Foreshore	Midland Meres and Mosses Phase 1
Midland Meres and Mosses Phase 2	Minsmere/ Walberswick	Morecambe Bay	Nene Washes	North Norfolk Coast	Northumbria Coast
Ouse Washes	Pagham Harbour	Pevensey Levels	Poole Harbour	Portsmouth Harbour	Redgrave and South Lopham Fens

Table D17: (Continued)

Natura200 and Ramsar (included in SAC and SPA)					
Ribble and Alt Estuaries	Rostherne Mere	Roydon Common	Rutland Water	Severn Estuary	Solent and Southampton Water
Somerset Levels and Moors	South West London Waterbodies	Stodmarsh	Stour and Orwell Estuaries	Teesmouth and Cleveland Coast	Thames Estuary and Marshes
Thanet Coast and Sandwich Bay	The Dee Estuary	The New Forest	The Swale	The Wash	Thursley and Ockley Bog
Upper Nene Valley Gravel Pits	Upper Solway Flats and Marshes	Walmore Common	Wicken Fen	Woodwalton Fen	
English Heritage					
Beeston Castle	Chester Castle: Agricola Tower and Castle Walls	Chester Roman Amphitheatre	Sandbach Crosses	Arbor Low Stone Circle and Gib Hill Barrow	Bolsover Castle
Bolsover Cundy House	Hardwick Hall	Hob Hurst's House	Nine Ladies Stone Circle	Peveril Castle	Sutton Scarsdale Hall
Wingfield Manor	Burton Agnes Manor House	Howden Minster	Skipsea Castle	Goodshaw Chapel	Sawley Abbey
Warton Old Rectory	Whalley Abbey Gatehouse	Ashby de la Zouch Castle	Jewry Wall	Kirby Muxloe Castle	Bolingbroke Castle
Gainsborough Old Hall	Gainsthorpe Medieval Village	Lincoln Medieval Bishop's Palace	Sibsey Trader Windmill	St Peter's Church, Barton-upon-Humber	Tattershall College
Thornton Abbey and Gatehouse	Aldborough Roman Site	Byland Abbey	Carlton Towers	Clifford's Tower	Easby Abbey
Fountains Abbey	Gisborough Priory	Helmsley Castle	Kirkham Priory	Marmion Tower	Middleham Castle
Mount Grace Priory	Pickering Castle	Piercebridge Roman Bridge	Richmond Castle	Rievaulx Abbey	St Mary's Church, Studley Royal

Table D17: (Continued)

English Heritage					
Scarborough Castle	Spofforth Castle	Stanwick Iron Age Fortifications	Steeton Hall Gateway	Wharram Percy Deserted Medieval Village	Wade's Causeway
Whitby Abbey	York Cold War Bunker	Mattersey Priory	Rufford Abbey	Acton Burnell Castle	Boscobel House and The Royal Oak
Buildwas Abbey	Cantlop Bridge	Clun Castle	Haughmond Abbey	Iron Bridge	Langley Chapel
Lilleshall Abbey	Mitchell's Fold Stone Circle	Moreton Corbet Castle	Old Oswestry Hill Fort	Stokesay Castle	Wenlock Priory
White Ladies Priory	Wroxeter Roman City	Brodsworth Hall and Gardens	Conisbrough Castle	Monk Bretton Priory	Roche Abbey
Croxden Abbey	Wall Roman Site				
Local nature reserves					
Brereton Heath	Burton Mill Wood	Clincton Wood	Cranberry Moss	Daresbury Firs	Dorchester Park
Hale Road Woodland	Helsby Quarry	Jacksons' Brickworks	Lindow Common	Marshall's Arms	Millennium Wood
Murdishaw Wood and Valley	Oxmoor Wood	Paddington Meadows	Pickerings Pasture	Poynton Coppice	Risley Moss
Rivacre Valley	Riverside Park, Macclesfield	Rixton Clay Pits	Runcorn Hill	Sound Common	Stanney Wood
Whitby Park	Wigg Island	Allestree Park	Ashover Rock (The Fabrick)	Badgers Hollow, Coton Park	Belper Parks
Bluebank Pools	Bluebell Woods	Breadsall Railway Cutting	Brearley Wetland	Brookfield Pond	Carr Wood
Chaddesden Wood and Lime Lane Wood	Chellaston Brickworks	Cromford Canal	Darley and Nutwood	Doe Lea	Duffield Millennium Meadow
Dunsley Meadows	Eddlestow Lot	Elm Wood	Elvaston	Ferneydale Grassland	Forbes Hole
Fox Covert	Goytside Meadows	Hammersmith Meadows	Highoredish Quarry	Manor Farm, Long Eaton	Matlock Parks

Table D17: (Continued)

Local nature reserves					
Mickleover Meadows	Mousley Bottom	Norbriggs Flash	Oakerthorpe	Pennytown Ponds	Pewit Carr
Pioneer Meadows	Pleasley Pit Country Park	Red River	Rowthorne Trail	Sinfin Moor	St Chad's Water
Stanton Gate	Stony Clouds	Straws Bridge	Stubbins Park	Sunnydale Park	The Sanctuary
Trowell Marsh	Watford Lodge	Wessington Green	West Park Meadows	Williamthorpe	Beverley Parks
Danes Dyke	Eastrington Ponds	Flamborough Outer Headland	Howden Marsh	Hudson's Way	Humber Bridge
Mayfield Broom	Millington Wood	Noddle Hill	Rockford Fields	Sigglesthorne Station	South Landing
Southorpe	Sugar Mill Ponds	Abney Hall	Alkrington Woods	Blackleach Country Park	Blackley Forest
Boggart Hole Clough, Charlestown	Borsdane Wood	Bridge Street	Broad Ees Dole	Brownstones Quarry	Captain's Clough
Castle Clough and Cowbury Dale	Chadkirk Country Estate	Chesham Woods	Chorlton Ess and Ivy Green	Chorlton Water Park	Clayton Vale, Clayton
Clifton Country Park	Cowbury Dale	Cunningham Clough	Doffcocker Lodge	Eagley Valley	Eatock Lodge
Etherow Country Park	Gatley Carrs	Glodwick Lows Nature Reserve	Great Wood	Greenslate Water Meadows	Hall Lee Bank Park
Hall Lee Brook	Happy Valley	Haslam Park, Bolton	Haughton Dale	Healey Dell	Heaton Mersey Common
Highfield Country Park, Levenshulme	Hollinwood Branch Canal	Hopwood Woodlands	Hulmes and Hardy Wood and Lower Haughton Meadows	Hurst Clough	Kersal Moor
Kirklees Valley	Kirkless	Knott Hill Reservoir	Levenhulme	Low Hall Park	Mersey Vale Nature Reserve
Moses Gate	Nob End	Ousel Nest Quarry	Pennington Flash	Philips Park	Poise Brook
Reddish Vale	Redisher Wood	Rocher Vale	Seven Acres	Stenner Woods and Milgate Fields	The Cliff (Kersal Dale)
The Wigan Flashes	Three Sisters (Salford)	Three Sisters (Wigan)	Trafford Ecology Park	Upper Bradshaw Valley	Woodbank Park
Worsley Woods	Wythenshawe Park	Alkincoats Woodland	Cross Hill Quarry	Deer Pond	Fishwick Bottoms

Table D17: (Continued)

Local nature reserves					
Foxhill Bank	Grange Valley	Greenfield	Haslam Park, Preston	Hic Bibi, Coppull Nature Reserve	Hills and Hollows
Hollins Vale	Lomeshaye Marsh	Longton Brickcroft	Lowerhouse Lodges	Lytham St Annes	Marton Mere
Mere Clough	Pleasington Old Hall Woods	Pope Lane and Boilton Wood	Preston Junction	River Darwen Parkway	Salthill Quarry
Sunnyhurst Woods	The Arran Trail	Trowbarrow Quarry	Upper Ball Grove Lodge	Warton Crag	Warton Crag Quarry
Withnell Fold	Withnell Nature Reserve	Aylestone Meadows	Billa Barra Hill Nature Reserve	Birstall	Bishop’s Meadow
Burbage Common and Woods	Glen Parva (Glen Hills)	Goss Meadows	Halstead Road Centenary Pasture	Humberstone Park	Kirby Frith
Knighton Spinney	Lucas Marsh	Moira Junction	Morley Quarry	Nature Alive	New Lount
North Kilworth	Reedbed	Saltersford Wood	Scraptoft	Snibston Grange	The Orchards
Watermead Country Park	Atkinsons Warren	Axholme Line-Haxey	Bradley and Dixon Woods	Brumby Wood	Cleethorpes Country Park
Cleethorpes Sands	Coningsby	Cross O’Cliff Orchard	Far Ings	Frodingham Railway Cutting	Havenside
Lollycocks Field	Mareham Pastures	Owlet Plantation	Owston Ferry Castle	Phoenix Parkway	Red Hill
Sawcliffe	Silica Lodge	Snipe Dales	South Thoresby Warren	Stanton’s Pit	Swanholme Lakes
The Pingle	The Shrubberies	Theaker Avenue	Vernatts Drain	Water’s Edge Country Park	Weelsby Woods Park
Whisby Nature Park	Willoughby Branch Line	Witham Way	Acornfield Plantation	Ainsdale and Birkdale Hills	Allerton (Eric Hardy)
Bidston Moss	Brookvale	Childwall Woods and Fields	Clinkham Wood Community Woodland	Colliers Moss	Croxteth
Dibbinsdale	Heswall Dales	Hilbre Island	Millwood and Alder Wood	Parr Hall Millennium Green	Ravenmeols Hills
Siding Lane Woodland	Stanley Bank	Thatto Heath Meadows	Thurstaston Common	Acomb Wood and Meadow	Ballowfield

Table D17: (Continued)

Local nature reserves					
Barlow Common	Birk Crag	Cleatop Park	Clifton Backies	Foxglove Covert	Freeholder's Wood and Riddings Field
Hell Wath	Hob Moor	Hookstone Wood	Langcliffe and Attermire	Nosterfield	Quarry Moor
Rossett Nature Reserve	St Nicholas Fields	The Dell	Alexandrina Plantation	Beeston Sidings	Bingham Linear Park
Bramcote Hills Park Woodland	Brecks Planatation	Brierly Forest Park	Brinsley Headstocks	Bulwell Hall Park Meadows	Clifton Grove, Clifton Woods & Holme Pit Pond
Cockglode and Rotary Wood	Colliers Wood	Colwick Woods	Daneshill Lakes (Gravel Pit)	Devon Park Pastures	Farndon Ponds
Gedling House Meadow	Gedling House Woods	Glapton Wood	Hall Om Wong Park	Harrison's Plantation	Hucknall Road Linear Walkway
Keyworth Meadow	King Georges Park	Langold Country Park	Martins Pond	Maun Valley Park	Meadow Covert
Moorbridge Pond and Springfield Corner	Netherfield Lagoons	Nottingham Canal	Oak Tree Heath	Oakham	Pleasley Vale (Meden Trail)
Portland Park	Quarry Lane	Rainworth Water	Ravensdale	Retford Cemetery	Rufford Country Park
Sandy Banks	Sandy Lane	Sellars Wood	Sharphill Wood	Sherwood Heath	Smithurst Meadows
Southwell Trail	Stapleford Hill Woodland	Sunrise Hill	Sutton Bonnington Spinney & Meadows	Teversal/Pleasley Network	The Bottoms, Meden Vale
The Carrs (Market Warsop)	The Hermitage	The Hook	Tippings Wood	Toton Fields	Vicar Water Nature Reserve
Watnall Green	Watnall Spinney	Wilwell Cutting	Woodsetts Pond	Brown Moss	Colemere
Coppice Leasowes, Church Stretton	Corbet Wood & Grinshill	Donington & Albrighton	Granville	Greenfields	Ifton Meadows
Limekiln Wood	Lodge Field	Madebrook Pools and Stirchley Dingle	Rea Brook Valley	Shelf Bank	Telford Town Park
The Ercall and Lawrence's Hill	Anston Stones Wood	Bowden Housteads Wood/Carbrook Ravine	Buntings Wood	Carlton Marsh	Catcliffe Flash

Table D17: (Continued)

Local nature reserves					
Centenary Riverside	Dearne Valley Park	Ecclesall Woods	Elsecar Reservoir	Firsby Reservoir	Fox Hagg
Gleadless Valley	Hatchell Wood	Loxley and Wadsley Common	Maltby Commons	Northcliffe Quarry	Old Denaby Wetland
Porter Valley Woodlands	Potter Holes Plantation	Roe Woods and Crabtree Pond	Salmon Pasture	Sandall Beat	Scholes Coppice and Keppel’s Field
Sharrow School Green Roof, Sheffield	Sheffield General Cemetary	Shire Brook Valley	Sunnybank	Town End Common	Warren Vale
West Haigh Wood	Wharncliffe Heath	Wheata Woods	Woodhouse Washlands	Woolley Wood	Worsbrough Country Park
Astonfields Balancing Lakes	Baggeridge Country Park	Bagnall Road Wood	Barlaston and Rough Close Common	Bateswood (North)	Bathpool Park
Berryhill Fields	Biddulph Valley Way (Whitemoor)	Bradwell Woods	Branston Water Park	Bridgetts Pool	Brocton
Brough Park Fields	Cecilly Brook	Christian Fields	Consall	Coyney Woods	Crown Meadow
Dosthill Park	Ferndown	Hales Hall Pool	Hartshill Park	Hazelslade	Hednesford Hills Common
Highgate Common	Hodge Lane	Hoften’s Cross Meadows	Holden Lane Pools	Kettlebrook	Kingfisher Trail
Kingsmead Marsh	Kingston Pool Covert (South)	Ladderedge Country Park	Marshes Hill Common	Pool Dam Marshes	Scalpcliffe Hill
Shoal Hill Common	Smith’s Pool	South Staffordshire Railway Walk	Stone Meadows	Tameside	Warwickshire Moor
Westport Lake	Whitfield Valley	Wom Brook Walk	Wyrley and Essington Canal	Alverthorpe and Wrenthorpe Meadows	Anglers Country Park
Beechwood Park	Ben Rhydding Gravel Pits	Breary Marsh	Bretton Country Park	Castle Hill	Chevet Branch Line
Chevin Forest Park	Colden Clough	Cromwell Bottom	Dalton Bank	Fairburn Ings	Farnley Hall Fishpond
Fitzwilliam Country Park	Gledholt Woods	Gorpley Clough	Haw Park Wood	Jerusalem Farm	Letchmire Pastures

Table D17: (Continued)

Local nature reserves					
Lower Spen Wildlife Area	Meanwood Valley	Middleton Woods	Milner Royd	Newmillerdam	Norland Moor
Notton Wood	Oakwell Park	Ogden Water	Pontefract Country Park	Pugneys Country Park	Railway Terrace
Scarr & Long Woods	Seckar Wood	Shibden Park & Cunnery Wood	Southern Washlands	Sparrow Wood	Stanley Marsh
Sun Lane	Sunny Bank Ponds	Tong Moor	Townclose Hills	Upper Park Wood	Upton Country Park
Walton Nature Park	Well Wood				

References

AMEC. **2013**. *Strategic environmental assessment for further onshore oil and gas licensing*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/consultations/environmental-report-for-further-onshore-oil-and-gas-licensing.

Andrews, I. J. **2013**. *The Carboniferous Bowland Shale gas study: geology and resource estimation*. *British Geological Society (BGS)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/226874/BGS_DECC_BowlandShaleGasReport_MAIN_REPORT.pdf.

BEIS. **2016**. *Digest of United Kingdom Energy Statistics 2016*. *Department for Business, energy and Industrial Strategy (BEIS)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/577712/DUKES_2016_FINAL.pdf.

BHA. **2017**. *Hydro facts* [Online] Wimborne, UK: British Hydro Association (BHA). Available: http://www.british-hydro.org/hydro_facts.html [Accessed August 2017].

Broderick, J., Anderson, K., Wood, R., Gilbert, P. and Sharmina., M. **2011**. *Shale gas: an updated assessment of environmental and climate change impacts*. *Tyndall Centre for Climate Change and Research*. Manchester, UK. Retrieved from: http://www.tyndall.ac.uk/sites/default/files/coop_shale_gas_report_update_v3.10.pdf.

Castell, S., Charlton, A., Clemence, M., Pettigrew, N., Pope, S., Quigley, A., Shah, J. N. and Silman, T. **2014**. *Public attitudes to science 2014*. *Ipsos MORI*. London, UK. Retrieved from: https://www.ipsos-mori.com/Assets/Docs/Polls/pas-2014-main-report.pdf.

Clark, C., Burnham, A., Harto, C. and Horner, R. **2013**. *Hydraulic fracturing and shale gas production: Technology, impacts, and regulations*. *Argonne National Laboratory*. Oak Ridge, TN, USA. Retrieved from: http://www.afdc.energy.gov/uploads/publication/anl_hydraulic_fracturing.pdf.

ComRes. **2015**. *Greenpeace fracking survey*. *ComRes*. London, UK. Retrieved from: http://www.comres.co.uk/polls/greenpeace-fracking-survey/.

Cooper, S. **2015**. Breaking - 1,000 jobs on way as Knottingley Power Station plans approved. *Pontefract and Castleford Express*, 10 March 2015, Available from: http://www.pontefractandcastlefordexpress.co.uk/news/breaking-1-000-jobs-on-way-as-knottingley-power-station-plans-approved-1-7148866.

Cunningham, N. **2014**. Why the debate over US LNG expoerts has been won. *oilprice.com* [Online]. Available: http://oilprice.com/Energy/Natural-Gas/Why-the-Debate-Over-U.S.-LNG-Exports-Has-Been-Won.html [Accessed: April 2017].

Czebiniak, M. **2014**. Women find careers in energy as downstream, petchems see growth. *Pittsborgh Post-Gazette*, August 12, 2014, Available from: http://powersource.post-gazette.com/powersource/companies/2014/08/12/Women-of-shale/stories/201408120004.

DECC. **2013a**. *Digest of United Kingdom energy statistics 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/279523/DUKES_2013_published_version.pdf.

DECC. **2013b**. *UK energy in brief 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224130/uk_energy_in_brief_2013.PDF.

DECC. **2013c**. *Updated energy and emissions projections 2013*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/239937/uep_2013.pdf.

DECC. **2015**. *DECC public attitudes tracking survey: Wave 15*. *Department of Energy and Climate Change (DECC)*. London, UK. Retrieved from: https://www.gov.uk/government/collections/public-attitudes-tracking-survey.

EDF Energy. **2017**. *West Burton B CCGT power station* [Online] Lonodn, UK: EDF Energy. Available: https://www.edfenergy.com/energy/power-stations/west-burton-b-ccgt [Accessed July 2017].

Fontenot, B. E., Hunt, L. R., Hildenbrand, Z. L., Carlton Jr., D. D., Oka, H., Walton, J. L., Hopkins, D., Osorio, A., Bjorndal, B., Hu, Q. H. and Schug, K. A. **2013**. An Evaluation of Water Quality in Private Drinking Water Wells Near Natural Gas Extraction Sites in the Barnett Shale Formation. *Environmental Science and Technology*, 47, 10032-10040.

Freyman, M. and Salmon, R. **2013**. *Hydraulic fracturing and water stress: Growing competitive pressures for water*. *Ceres*. Boston, MA, USA. Retrieved from: http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers.

Google Earth. **2015.** UK *Google Earth 7.1.5.1557 Google Earth 7.1.5.1557* Google Inc:

Hendry, C. **2011**. *New power stations bring jobs to Yorkshire* [Online] London, UK: Department of Energy and Climate Change (DECC). Available: https://www.gov.uk/government/news/new-power-stations-bring-jobs-to-yorkshire [Accessed July 2017].

House of Lords. **2014**. *The economic impact on UK energy policy of shale gas and oil*. May, 2014. *House of Lords: Economic Affairs Committee*. London, UK. Retrieved

from:
http://www.publications.parliament.uk/pa/ld201314/ldselect/ldeconaf/172/172.pdf.

HSE. **2014**. *Annual offshore statistics and regulatory activity report 2013/2014*. *Health and Safety Executive (HSE)*. London, UK. Retrieved from: http://www.hse.gov.uk/offshore/statistics/hsr1314.pdf.

HSE. **2017**. *Index of data tables.* Health and Safety Executive (HSE): London, UK (August 2017) Retrieved from: http://www.hse.gov.uk/Statistics/tables/index.htm.

Lewis, C., Speirs, J. and MacSweeney, R. **2014**. *Getting ready for UK shale gas: Supply chain and skills requirements and opportunities*. *United Kingdon Onshore Oil and Gas and Ernst and Young*. London, UK. Retrieved from: http://www.ey.com/Publication/vwLUAssets/Getting_ready_for_UK_shale_gas/$FILE/EY-Getting-ready-for-UK-shale-gas-April-2014.pdf.

Lutz, B. D., Lewis, A. N. and Doyle, M. W. **2013**. Generation, transport, and disposal of wastewater associated with Marcellus Shale gas development. *Water Resources Research*, 49, 647-656.

Maritime Connector. **2017**. *Bulk carrier* [Online] Rijrka, HR: Maritime Connector. Available: http://maritime-connector.com/bulk-carrier/ [Accessed July 2017].

McGrath, K. and Marinelli, M. **2012**. *Female workforce participation in the Australian oil and gas industry- a global comparison (Conference)*. 2012 APPEA National Oil and Gas Conference. 2012 Perth, AU.

Ministry of Public Health (State of Qatar). **2017**. *Occupational health* [Online] Doha, QA: Ministry of Public Health (State of Qatar). Available: https://phs.moph.gov.qa/data/occupational-health/ [Accessed August 2017].

Mishra, B. C. K. and Singh, A. K. **2015**. *Renovation, modernization and upgradation of old hydro power station- a way forward to sustainable development*, ed. Dehradun, IN: Published.

Mott MacDonald. **2010**. *UK electricity generation costs update*. *Department of Energy and Climate Change (DECC)*. Brighton, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65716/71-uk-electricity-generation-costs-update-.pdf.

National Grid. **2017**. *Report for the year ended 31 March 2017*. *National Grid*. London, UK. Retrieved from: http://investors.nationalgrid.com/~/media/Files/N/National-Grid-IR/results-centre/full-year-results-statement-2016-17.pdf.

npower. **2017**. *RWE in the UK: CR Report*. *npower*. Swindon, UK. Retrieved from: https://www.npower.com/home/about-npower/our-responsibility/.

O'Hara, S., Humphrey, M., Andersson-Hudson, J. and Knight, W. **2015**. *Public perception of shale gas extraction in the UK: Two years on from the Balcombe protests*. *University of Nottingham*. Nottingham, UK. Retrieved from:

http://bettersociety.net/images/Public%20Perceptions%20of%20shale%20gas%20in%20the%20UK%20sept131015MH.WK.JA-H.pdf.

Oil & Gas UK. **2011**. *2011 UKCS workforce demographics report*. January, 2015. *Oil and Gas UK*. London, UK. Retrieved from: http://www.oilandgasuk.co.uk/cmsfiles/modules/publications/pdfs/EM010.pdf.

Oram, B., Halsor, S. and Redmond, B. **2011**. *Pennsylvania drinking water quality- Your private well: What do the results mean?*, Second, Wilkes-Barre, PA, USA: Wilkes University.

Orem, W., Tatu, C., Varonka, M., Lerch, H., Bates, A., Engle, M., Crosby, L. and McIntosh, J. **2014**. Organic substances in produced and formation water from unconventional natural gas extraction in coal and shale. *International Journal of Coal Geology*, 126, 20-31.

Parsons Brinckerhoff. **2013**. *Electricity generation cost model- 2013 update of non-renewable technoligies*. *Department of Energy and Climate Change (DECC)*. Manchester, UK. Retrieved from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/223634/2013_Update_of_Non-Renewable_Technologies_FINAL.pdf.

Qatargas. **2017**. *Future fleet* [Online] Doha, QA: Qatargas. Available: http://www.qatargas.com/English/AboutUs/Pages/FutureFleet.aspx [Accessed July 2017].

Rigzone. **2014**. *Search for job opportunities* [Online] Houston, TX, USA. Available: http://www.rigzone.com/jobs/search_jobs.asp [Accessed April 2017].

South Hook LNG Terminal. **2017**. *How it works* [Online] Milford Haven, UK: South Hook LNG Terminal Company Ltd. Available: https://www.southhooklng.com/liquefied-natural-gas/the-supply-chain/how-it-works/ [Accessed July 2017].

Spence, A., Venables, D., Pidgeon, N., Poortinga, W. and Demski, C. **2010**. *Public perceptions of climate change and energy futures in Britain: Summary of findings of a survey conducted from January 2010 to March 2010*. *University of Cardiff*. Cardiff, UK. Retrieved from: http://psych.cf.ac.uk/understandingrisk/docs/final_report.pdf.

Stamford, L. and Azapagic, A. **2012**. Life cycle sustainability assessment of electricity options for the UK. *International Journal of Energy Research*, 36, 1263-1290.

Standards for Highways. **1997**. *Traffic flow ranges for use in the assessment of new rural roads*. Standards for Highways. London, UK.

Standards for Highways. **1999**. *Traffic capacity of urban roads*. Standards for Highways. London, UK.

Statkraft. **2017**. *Rheidol power station* [Online] Oslo, NO: Statkraft. Available: https://www.statkraft.com/about-statkraft/visitor-centres/rheidol-visitor-centre/ [Accessed July 2017].

UK water projects online. **2015**. *Water company* [Online] Lancaster, UK. Available: http://www.waterprojectsonline.com/water_company.htm [Accessed July 2015].

Williams, J., Field, L. and Lee, E. **2011**. *The impact of unconventional gas in Europe: A report to Ofgem*. *Poyry (for Ofgem)*. Warrington. Retrieved from: https://www.ofgem.gov.uk/ofgem-publications/38113/033publicreportunconventionalgasofgemlogov41.pdf.

Wire and staff reports. **2008**. Poll shows public support for LNG pipeline. *Mail Tribune* [Online]. Available: http://www.mailtribune.com/article/20081203/NEWS/812030326#ReaderReaction [Accessed: April 2017].

Appendix E

EI. The SMART method

The relative importance of a sustainability aspect or indicator is represented by its weighting. The weighting is calculated relative to the other aspects/indicators in the same category. To calculate the weighting, each aspect or indicator is first scored by the MCDA practitioner (in this work the practitioner is the thesis author), with a score of ten indicating the least important aspect/indicator and the more important ones assigned higher scores. The scores for all the aspects or indicators in a given category are then summed up and the weighting of each aspect and indicator calculated according to equations (E1) and (E2), respectively:

$$W_a = \frac{I_a}{\sum_a^A I_a} \tag{E1}$$

$$W_b = \frac{I_b}{\sum_b^B I_b} \tag{E2}$$

where:

W_a the weighting of sustainability aspect *a* (environmental, economic or social)

I_c the importance of aspect *a*

a sustainability aspect

A total number of aspects

W_b the weighting of sustainability indicator *b*

I_b the importance of indicator *b*

b sustainability indicator

B total number of indicators.

The options considered, in this case different electricity options, are rated based on their performance in each indicator and the ratings are calculated using a value function. The worst performing option is given a rating of zero and the best a rating of one. The remaining options are rated between these two values, in the order of their performance. The ratings vary depending on the type of value function used. A linear value function assumes that the changes from worst to best are linear. However, it does not take into consideration large gaps in between. Non-linear value functions can also be used when the distribution of scores is not even, or there are outliers or gaps in the distribution. An exponential value function using the bisection method was selected for this work. In this method, the difference between the worst and the bisection point is of equal importance to the difference between the bisection point and the highest value, enabling consideration of large gaps.

The overall sustainability score is calculated for each option based on the estimated weightings of the sustainability aspects and indicators and the ratings of the options, as follows:

$$S_o = \sum_a^A W_a \times \left(\sum_b^B W_b \times R_{o,b} \right) \qquad \text{(E3)}$$

where:

S_o overall sustainability score of option *o*

$R_{o,b}$ rating of option *o* for indicator *b*

The options are then ranked, with the one with the highest score being the most sustainable and the one scoring the lowest, the least sustainable.

EII. Sustainability indicators

Table E1: Description of indicators used in the MCDA.

Indicator	Units[a]	Description
Abiotic depletion of elements (ADP_e)	kg $Sb_{-Eq.}$/kWh	Potential for depletion of elemental metals and minerals
Abiotic depletion of fossil fuels (ADP_f)	MJ/kWh	Potential for depletion of fossil fuels
Acidification potential (AP)	kg $SO_{2-Eq.}$/kWh	Potential for acid deposition and formation in water and terrestrial ecosystems
Eutrophication potential (EP)	kg $PO_{4-Eq.}$/kWh	Potential for over-fertilisation of aquatic and terrestrial ecosystems
Freshwater aquatic ecotoxicity (FAETP)	kg $DCB_{-Eq.}$/kWh	Potential for release of substances toxic to freshwater water environments
Global warming potential (GWP)	kg $CO_{2-Eq.}$/kWh	Potential for release of greenhouse gases
Human toxicity potential (HTP)	kg $DBC_{-Eq.}$/kWh	Potential for release of substances toxic to human health into the environment
Marine aquatic ecotoxicity potential (MAETP)	kg $DCB_{-Eq.}$/kWh	Potential for release of substances toxic to marine water environments
Ozone depletion potential (ODP)	kg $R11_{-Eq.}$/kWh	Potential for emissions of ozone depleting substances
Photochemical oxidant creation potential (POCP)	kg $C_2H_{2-Eq.}$/kWh	Potential for creation of photochemicals
Terrestrial ecotoxicity potential (TETP)	kg $DCB_{-Eq.}$/kWh	Potential for release of substances toxic to terrestrial environments
Levelised cost of electricity (LCOE)	p/kWh	The ratio of total financial inputs required to generate electricity to the total amount of electricity generated by the power plant
Capital cost	p/kWh	The ratio of total capital required to build a power plant to the total amount of electricity generated
Fuel cost	p/kWh	The ratio of total cost for fuel incurred by a power plant to the total amount of electricity generated
Direct employment (DE)	person-years/kWh	The ratio of total number of jobs created in the whole lifecycle to the total amount of electricity generated
Worker injuries (WI)	injuries/kWh	The ratio of injuries to employees (in the whole lifecycle) to total amount of electricity generated, calculated based on employment in the whole life cycle
Public support index (PSI)	%	Attitude towards electricity generation options, giving an indication of net support
Diversity of fuel supply (DFS)	no units	Measure of energy security, indicating the dependence on foreign imports to meet energy needs

[a]DCB: dichlorobenzene; R11:tricholorofluoromethane.

EIII. Pedigree matrix

Table E2: Pedigree matrix characteristics and criteria used to grade data quality (Althaus et al., 2007; Weidema et al., 2013).

	Score				
Criteria	*1*	*2*	*3*	*4*	*5*
Reliability	Published data based on measurements	Published data partially based on assumptions *Or* Non-published data based on measurements	Non-published data based on estimates	Estimates verified by experts	Non-verified estimates
Completeness	Representative of all relevant sites for market considered, over an adequate time period	Representative of ~50% relevant sites for market considered, over an adequate time period	Representative of <50% relevant sites for market considered, over an adequate time period *Or* Representative of >50% relevant sites for market considered, short time period	Representative of only one site relevant for market considered, over an adequate time period	Representativeness unknown
Temporal correlation	≤ 3 years difference between data and study	≤ 6 years difference between data and study	≤ 10 years difference between data and study	≤ 15 years difference between data and study	≥3 years difference between data and study, or age unknown
Geographical correlation	Area of study	Larger area including study area	Similar area	Slightly similar area	Unknown or distinctly different area
Further technological correlation	Data for technology from company/operator	Data not from company/operator but for same technology	Data on similar processes and materials but different technology	Data on similar processes and materials	Data on similar processes and material but laboratory scale
Sample size	> 100 measurements	> 20 measurements	> 10 measurements	≥ 3 measurements	Unknown

EIV. Variations in the values of sustainability indicators across the electricity options

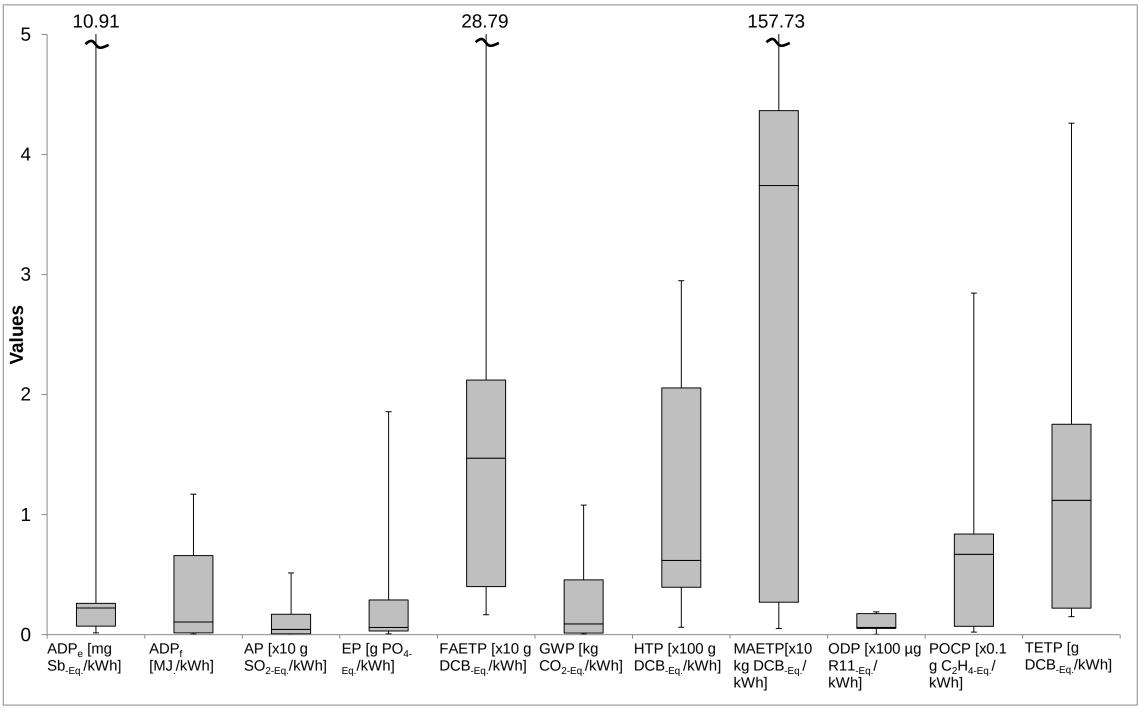


Figure E1: Variations in the environmental impacts for all nine electricity options considered in the study.

[Data obtained from Chapter 3. The box plots show median (horizontal line) and first and third quartiles (bottom and top of the boxes) of the values. The whiskers indicate the minimum and maximum values. For indicator acronyms, see Table E1.]

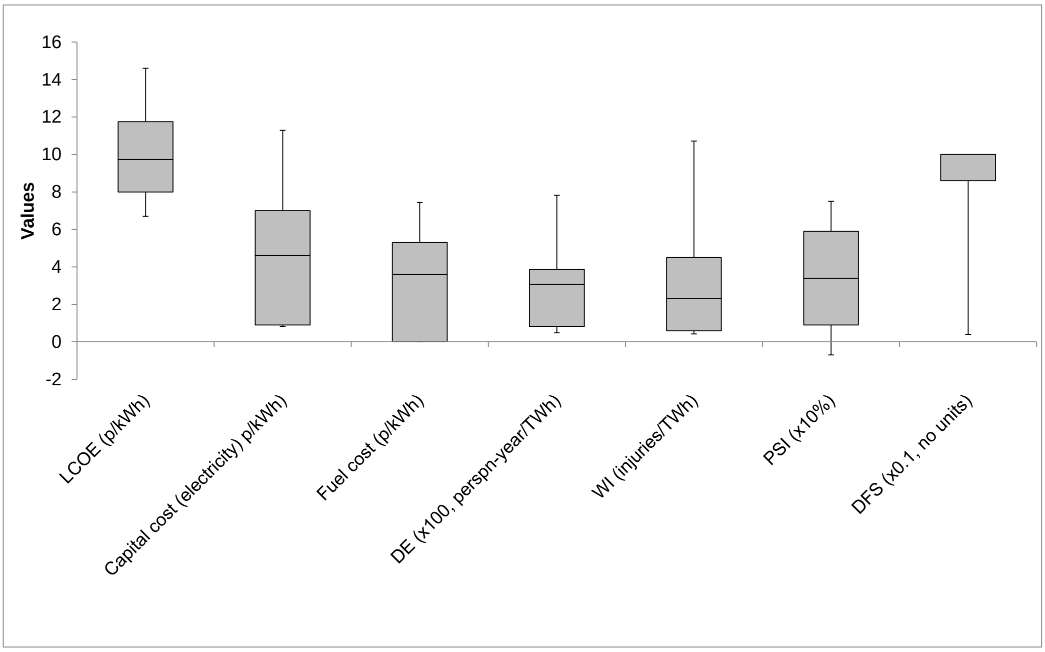


Figure E2 : Variations in the economic and social impacts for all nine electricity options considered in the study.

[Data obtained from chapters 4 and 5. The box plots show median (horizontal line) and first and third quartiles (bottom and top of the boxes) of the values. The whiskers indicate the minimum and maximum values. For indicator acronyms, see Table E1.]

EV. Data quality assessment

Table E3: Pedigree matrix results for literature data sources.

Literature LCI data[a]	No. of data sources	Reliability[b]	Completeness[b]	Temporal correlation[b]	Geographical correlation[b]	Technological correlation[b]	Sample size[b]	Total
LCA[a] – overall data quality (average)		***3.06***	***1.25***	***1.26***	***1.8***	***1.75***	***4.7***	***13.82***
Shale gas extraction	8	1.63	2.25	1.63	5.00	1.75	3.50	15.76
Power plant	1	4.00	1.00	1.00	1.00	2.00	5.00	14.00
Conventional gas	1	4.00	1.00	1.00	1.00	2.00	5.00	14.00
Liquefied natural gas	3	1.67	1.00	1.67	1.00	1.00	5.00	11.34
Power plant (other electricity options)	1	4.00	1.00	1.00	1.00	2.00	5.00	14.00
LCC[a] – overall data quality (average)		***2.17***	***1.00***	***1.08***	***1.00***	***1.83***	***5.00***	***12.08***
Capital cost	5	2.00	1.00	1.00	1.00	2.00	5.00	12.00
Operating cost	2	2.00	1.00	1.00	1.00	2.00	5.00	12.00
Labour	2	2.00	1.00	1.00	1.00	2.00	5.00	12.00
Community charter	1	3.00	1.00	1.00	1.00	1.00	5.00	12.00
Power plant costs	2	2.00	1.00	1.50	1.00	2.00	5.00	12.50
Levelised cost (other electricity options)	1	2.00	1.00	1.00	1.00	2.00	5.00	12.00
SSA[a] – overall data quality (average)		***1.36***	***1.04***	***1.44***	***2.37***	***1.52***	***3.71***	***11.43***
Public support	7	1.57	1.57	1.29	2.14	1.29	2.14	10.00
Worker injury	3	1.00	1.00	1.33	1.00	1.33	5.00	10.66
Direct employment	19	1.74	1.00	1.84	1.42	1.56	5.00	12.56
Local employment	2	1.50	1.00	1.00	3.00	2.00	3.50	12.00
Diversity of fuel supply	8	1.50	1.00	1.00	1.38	1.13	5.00	11.01

Table E3: (Continued)

Literature LCI data[a]	No. of data sources	Reliability[b]	Completeness[b]	Temporal correlation[b]	Geographical correlation[b]	Technological correlation[b]	Sample size[b]	Total
Noise	3	1.00	1.00	1.00	3.67	1.67	5.00	13.34
Traffic	1	2.00	1.00	2.00	5.00	2.00	5.00	17.00
Land use conflict	1	1.00	1.00	1.00	1.00	1.00	1.00	6.00
Wastewater volume	2	1.50	1.00	1.00	5.00	2.00	3.00	13.50
Wastewater treatment	3	1.33	1.00	1.33	3.67	2.00	2.67	12.00
Media bias	5	1.00	1.00	1.00	1.00	1.00	1.00	6.00
Regulation (US)	3	1.00	1.00	2.00	5.00	2.00	1.00	12.00
Regulation (UK)	1	1.00	1.00	2.00	1.00	1.00	5.00	11.00
Gender equality	3	1.67	1.00	1.67	1.67	1.33	5.00	12.34
Spending on local supplies	1	2.00	1.00	1.00	1.00	2.00	5.00	12.00
Direct community investment	4	1.00	1.00	2.50	1.00	1.00	5.00	11.50
Future scenarios – overall data quality		***1.88***	***1.00***	***1.75***	***1.47***	***1.03***	***5.00***	***12.13***
Gas mix	1	2.00	1.00	2.00	2.00	1.00	5.00	13.00
Electricity mix	2	2.00	1.00	2.00	1.50	1.00	5.00	12.50
Levelised cost (other electricity options)	1	2.00	1.00	2.00	1.00	1.00	5.00	12.00
Diversity of fuel supply	8	1.50	1.00	1.00	1.38	1.13	5.00	11.01

[a] LCI: life cycle inventory; LCA: life cycle assessment; LCC: life cycle cost; SSA: social sustainability assessment.
[b] Average values for the number of data sources used.

Table E4: Pedigree matrix results for Ecoinvent data sources.

Ecoinvent LCI data (LCA only)[a]	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation	Sample size	Total
Shale gas	1	1	3	2	2	1	10
Conventional gas	1	1	4	2	2	1	11
Liquefied natural gas	1	1	4	2	2	1	11
Coal	1	2	4	2	3	1	13
Nuclear	1	1	5	3	2	1	13
Hydro	1	2	4	2	2	1	12
Solar PV	1	1	3	2	2	1	10
Wind	1	1	4	3	2	1	12
Biomass	1	2	4	4	3	1	15

Nomenclature

a	sustainability aspect
A	total number of aspects
b	sustainability indicator
B	total number of indicators
I_b	the importance of indicator b
I_c	the importance of aspect a
$\mathrm{R}_{\mathrm{o,b}}$	rating of option o for indicator b
S_{o}	overall sustainability score of option o
W_a	the weighting of sustainability aspect a (environmental, economic or social)
W_b	the weighting of sustainability indicator b

References

Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Roland Hischier, Nemecek, T., Rebitzer, G., Spielmann, M. and Wernet, G. **2007**. *Overview and methodology: Data v2.0 (2007)*. *The ecoinvent Centre*. Zurich, CH. Retrieved from: http://www.ecoinvent.org/database/older-versions/ecoinvent-version-2/methodology-of-ecoinvent-2/methodology-of-ecoinvent-2.html.

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O. and Wernet, G. **2013**. *Overview and methodology: Data quality guideline for ecoinvent database version 3 (final)*. *The ecoinvent Centre*. Zurich, CH. Retrieved from: https://www.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf.