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SUSTAINABILITY OF SHALE GAS COMPARED TO OTHER ENERGY FUELS

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CRANFIELD UNIVERSITY

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SCHOOL OF APPLIED SCIENCES
Economics for Natural Resource and Environmental Management

MASTER OF SCIENCE
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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

Although there have been several studies evaluating the potential impact of shale gas, there are still on-going concerns and debate about the environmental risks and uncertainties associated with shale gas extraction and exploitation. In the meantime, there is to date little information on the sustainability of shale gas compared with other energy fuel sources. The aim of this study was to assess and compare the sustainability of shale gas with other energy fuels including natural gas, coal and nuclear energy and to examine the economic potential of shale gas for Europe.

The developed sustainability indices for each energy fuel considered showed that shale gas is less sustainable when compared to nuclear energy or conventional natural gas. This is mainly caused by higher emissions release during upstream processes and the associated risk of health problems. The analysis however showed that when compared to coal shale gas is a much more sustainable alternative. Coal is from the sustainability perspective the worst option across all energy sources.

Potential benefits of shale gas development in Europe are significant. These include job creation, GDP contribution, lower energy prices, reduced EU import dependency and consequently the overall competitiveness of the European region.

However, before Europe sees any significant production in shale gas many developments have to take place. Governments have to send positive signals to potential investors by investing in research and development as further exploration and appraisal of the shale gas resources have to be carried out. Further research is also needed to fully understand the impact of shale gas on the environment, communities, health and welfare.

Keywords: coal, natural gas, nuclear energy, sustainability indicators, shale gas development, sustainability index

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EU	European Union
USA	United States of America
US	United States
LNG	Liquefied natural gas
GHG	Greenhouse gas
UK	United Kingdom
GDP	Gross Domestic Product
R&D	Research and Development
O&M	Operating and maintenance

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Sustainability of shale gas compared to other energy fuels

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Abstract

Although there have been several studies evaluating the potential impact of shale gas, there are still on-going concerns and debate about the environmental risks and uncertainties associated with shale gas extraction and exploitation. In the meantime, there is to date little information on the sustainability of shale gas compared with other energy fuel sources. The aim of this study was to assess and compare the sustainability of shale gas with other energy fuels including natural gas, coal and nuclear energy and to examine the economic potential of shale gas for Europe.

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Introduction

The “World and European Energy and Transition Outlook” (EU, 2011a) estimates that the total global energy requirements in 2100 will be three times higher than the current energy requirements. The majority of the energy demand over the next few decades is still anticipated to be supplied by the fossil fuels with natural gas playing a key role. Natural gas is a preferred option for energy-efficient electricity production as it has lower environmental impact when burn compared with coal and consequently it offers an opportunity to reduce significantly CO_2 emissions (Hultman et al., 2011; Rivard et al., 2014).

Unconventional natural gas, also known as shale gas, is natural gas, mostly methane, tightly trapped inside shale rock. The world “unconventional” refers to the way how the gas is extracted. Conventional gas is found in permeable rocks and can be extracted freely after drilling; the unconventional gas is trapped in impermeable rock formations such as shale, coal beds or tight sands (UNEP, 2012). In the past unconventional gas was not technically and economically viable to extract but the recent technological advancement combining horizontal drilling and hydraulic fracturing has made it possible (Wang et al., 2014). As the levels of conventional gas are gradually decreasing producers are looking at shale gas to secure energy supply.

In the last decade the USA has seen a rapid growth in unconventional natural gas extraction (Figure 1; Rivard et al., 2014). The total shale gas production in 2013 was 0.26 trillion cubic metres, compared to only 0.014 in 2003 (Figure 1). Between 2007 to 2012 shale gas production in the USA has grown on average by 51% every year and the price of natural gas during this time period has dropped by two-third (Lund et al., 2013).

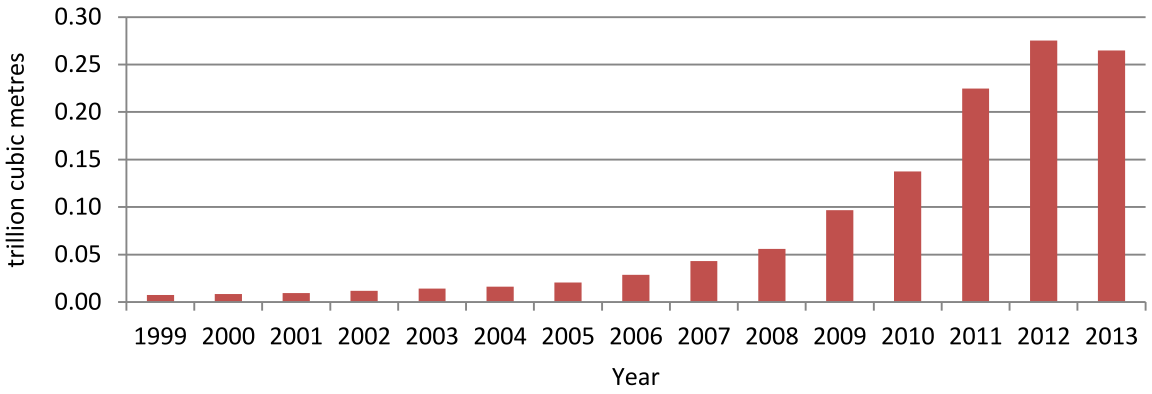

Figure 1 U.S. Shale gas production from 1999 to 2013 (trillion cubic metres) (source: Statista, 2014)

The USA is now the biggest natural gas producer worldwide and together with Canada accounts for one quarter of the total global natural gas production. The importance of shale gas is expected to be ever-increasing as it is estimated that its share on the total US gas production could rise to 49% by 2035 (up from 23% in 2010). These estimates highlight the potential significance of shale gas in the US energy mix in the future (Stark, 2012; Regeneris Consulting, 2011). Furthermore, the reserves found in the USA are estimated to be large enough to free the country from decades-long dependency on imports of natural gas (Rivard et al., 2014). The USA should be in the position to be a net exporter of gas in 2018 and a net exporter of liquefied natural gas (LNG) in 2016 (BP, 2014). Shale gas extraction development can have an immense impact on geopolitics and energy security. Countries which used to be a net importer of natural gas can suddenly become a net exporter (KPMG, 2012). The energy security concerns have played a very important role in the shale gas development boom in the USA.

Although shale gas extraction in the USA is not the only reason for natural gas price drop (e.g. reduced demand as a consequence of the financial crisis) it has played a significant role in driving gas prices down. Development of shale gas has made natural gas prices lower and as such has had a positive impact on the US overall economy (Asche et al., 2012). Lower and less volatile prices have brought benefits to American consumers in form of reduced household costs and have also benefited US competitive and strategic interests due to revitalization of numerous domestic industries (Stark, 2012).

Shale gas development has also a positive impact on employment. It is estimated that shale gas exploration in the USA in 2010 supported directly more than 150,000 jobs. When jobs created indirectly or as a consequence of induced expenditure are also considered the total number of jobs created rises to 600,000 (ANGA, 2014). It is anticipated that by 2020 the shale gas production could create around 1.7 million permanent jobs and add up to 4% to the US Gross Domestic Product (GDP) (Lund et al., 2013).

According to the US Energy Information Administration (EIA, 2013a) there are also high reserves of shale gas in European countries with Poland, France and Russia having the highest recoverable resources. Other European countries such as Ukraine, Romania or United Kingdom are also assumed to have significant reserves. However, Europe might not see such a drastic revolution in shale gas production as seen in the USA. Although there are high shale gas reserves the context within the European countries is very different. Europe seems to be more environmentally oriented and as there are many questions concerning environmental impact of shale gas, Europe might not be as inclined to shale gas production as the USA (Stevens, 2012). The challenges that shale gas is facing in Europe seem to be greater than in the USA. One of the reasons might be a different population density which is higher in Europe. More people would be disrupted and directly impacted by shale gas extraction than in the USA and therefore their acceptance towards this method might be lower. In some cases people might want the resources to be developed and would use them but do not want them to be developed near their homes – such a phenomena known as “not in my back yard” (NIMBY) (Asche et al. 2012; Christopherson and Rightor, n.a).

The main reason of different contexts for shale gas development however lies in the property rights associated with gas. While in Europe the subsoil minerals are in the ownership of the country, in the USA they are the property of the landowner (Stevens, 2012). Landowners in the USA receive a significant monetary incentive to allow extraction companies to carry on with the operations. Numerous landowners in the USA have become so–called “shaleionaires” due to shale gas exploration (CBS News, 2010).

Nevertheless, there are many factors that are driving the development of shale gas in Europe. The main drivers are linked to the energy security and dependency on foreign sources of primary fuels. Extraction of shale gas reserves has been seen as the potential solution to these concerns. Perhaps more than other European countries, Poland is very interested in shale gas extraction development as it is seeking to reduce its energy dependency on Russia (KPMG, 2012). Poland has a great potential for developing shale gas industry and the government has been issuing licences for shale gas extraction. The country shale gas reserves could make Poland energy self-sufficient (EU, 2012).

The United Kingdom would be also keen to develop shale gas industry. The shale gas resources in the UK were estimated to be almost 37 trillion cubic metres. For comparison, the UK´s annual natural gas consumption is around 0.1 trillion cubic metres. The question however is how much of these resources are technically and economically recoverable. But even if it was only 10% it would still supply the United Kingdom for almost 40 years (at the current consumption level) (ENDS, 2013).

If Poland, the United Kingdom and other European countries were able to develop the commercial shale gas production the Russian influence in Europe energy market would significantly decrease. Russia is aware of the potential threats and could use its dominance of the conventional gas to create obstacles for companies looking to develop shale gas production in the region. Russian politicians have already been heard in European debates questioning the environmental safety of shale gas. In the past, Europe has been on numerous occasions held in hostage to decrease gas supplies due to disputes between Russia and Ukraine (KPMG, 2012).

For the shale gas to become “game changer” in Europe as seen to high extent in the USA, the industry have to go through reputational and regulatory obstacles. There are still many operational, financial and environmental unknown variables and risks that could impact the future viability of shale gas extraction both in the USA and Europe. Natural gas prices in the USA have dropped to a level which makes it very difficult for some wells to be still operating profitably (Erismann, 2011). Furthermore, the costs associated with extraction in Europe are likely to be higher than in the USA. Conventional gas production on land in the USA is declining and as a consequence there is an access to substantial and inexpensive drilling capacity. Not such a capacity is available in Europe. Furthermore, lack of suitable technical personnel, access to suppliers, special equipment and infrastructure could also drive extraction costs high (Asche et al., 2012). The big question is also what impact the further shale gas development will have on the renewable sources in Europe especially when taking into consideration its ongoing endeavour to achieve a low-carbon economy. The European Union member states have committed themselves to reducing GHG emissions by 20%, increasing the share of renewable energy in the EU´s energy mix to 20% and achieving the 20% energy efficiency by 2020 (EU, 2011b). There are two contradicting views on this issue. The first one claims that renewables and nuclear would not be displaced. According to this view there is a need for low-carbon forms of energy for the future and because renewables are expensive at the moment shale gas will serve as a transition to enable renewables to become cost competitive (Economic Affairs Committee, 2014). Renewable industry should not feel concern as shale gas is in this case seen as a “blue bridge” to a green future (The Climate Group, 2013). The opposite view is that shale gas development will have a negative effect on renewables because it will divert investments away from them. In this case the renewable energies are seen as a victim of shale gas development (Harvey, 2012; EREC, 2013). At this point it is very difficult to say which of these two opinions or views is more likely to be the case.

Nevertheless, shale gas is considered as the cleanest out of all fossil fuels. Compared to coal, it burns about 50% less of carbon dioxide and 75% less of nitrogen oxide. Furthermore, it emits almost no black carbon, sulphur dioxide, particulates, carbon monoxide and mercury (Jenner and Lamadrid, 2013).

Some argue that shale gas could fulfil the “energy triangle” – security of supply, affordability and environmental protection (Jenner and Lamadrid, 2013).

However, there have been on-going concerns and debate about the environmental impact linked to shale gas extraction. One of the main concerns is water pollution. During the hydraulic fracturing high volume of water containing chemicals is pumped under high pressure into the well to fracture the shale. Fracking can be very water intensive and the volume of water needed for fracturing can vary depending on the water management method used. Some studies indicate that between 2 to 10 million gallons of water might be needed (IEA, 2012; Inglesby et al. (2012); Boudet et al. 2014). Water contamination is another major concern. Evidence of water contamination by shale gas has been found in the USA (UNEP, 2012). Fugitive emissions of methane associated with shale gas have also raised some concerns. The comparative impact of methane (CH4) on climate change is over 25 times greater than CO_2 on 100 year timescale and 72 times greater on 25 year time scale (IPPC, 2007). Some argue that given the need to reduce the global emissions in the coming decades the 20-year timescale should be used instead of commonly used 100-year horizon when analysing the potential environmental impact of shale gas (Howarth et al., 2011). If the total emissions of shale gas production were compared from the 20-year perspective some studies claim that shale gas would lead to increase of climate warming and would be comparable to coal only over a 100-year time horizon (Wigley, 2011; Burnham et al., 2011; Howarth et al., 2011). However, many scientists have stepped to challenge this finding claiming that the estimated methane emissions used in these studies exceed any reasonable estimate and should be seen as an outlier (AEA, 2012; MacKay and Stone, 2013; Cathles et al., 2012).

It is not questionable that there are potential environmental benefits but also potential environmental consequences linked to shale gas extraction. Shale gas development has gained large media attention in the USA and the rapid growth of shale gas development has been matched by rapid increase in misinformation about potential environmental threats (AEA, 2014). This has marred the reputation of the global unconventional gas industry and has made it difficult to address concerns among investor, politicians and the public about the scale and probability of negative impacts. It is important to distinguish which of these threats are based on misunderstanding and which ones are real.

In order to build public confidence in the extraction method full transparency must be implemented by the producers and the industry as a whole. The rigorous standards of well operations such as soundness of well casings and best practices in terms of wastewater disposal must be put in place. If this is not done, then the hydraulic fracturing might be prohibited or stopped as seen recently in some European countries like France in 2011 and Bulgaria in 2012 (Lund et al., 2013; BBC, 2012).

Shale gas is seen by many as transitional gas to low carbon economy but there is still an uncertainty related to shale gas development. Many studies have been carried out evaluating the impact of shale gas. Not many of these studies however focus on comparing the sustainability of shale gas with other energy sources such as coal, conventional natural gas and nuclear power. There is a gap of information which would provide a comprehensive analysis of overall sustainability (taking into consideration economic, environmental and also societal perspective) of shale gas compared to other energy carriers. The aim of this paper is to address this gap by comparing sustainability of shale gas with other energy fuels and examine the potential of shale gas as a future energy source for Europe.

The paper is divided into five sections. The section 1 provides an overview of the environmental footprint of the different stages of shale gas production. The Section 2 compares the context of shale gas development in USA and Europe. Potential trade-offs of shale gas are described in the third section. Data and methodology for comparing sustainability of shale gas with other energy carriers are presented and analysed in Section 4 with the results reported in Section 5. Conclusions drawn from the analysis are described in Section 6.

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1 Shale gas extraction process

Shale gas extraction is a very complex and sophisticated process which involves high capital expenditure, large volumes of skilled labour, significant greenhouse gas (GHG) emissions and potential environmental risks (Regeneris Consulting, 2011). Figure 2 shows the main operational activities related to shale gas processing in the upstream phase and the environmental compartments potentially affected. Few activities have to take place before a shale gas well is prepared for production. These include site preparation, drilling and hydraulic fracturing, well completion and storage and disposal of fracturing fluids and flowback. Each of these activities is different in terms of time, costs, associated GHG emissions and potential environmental impact.

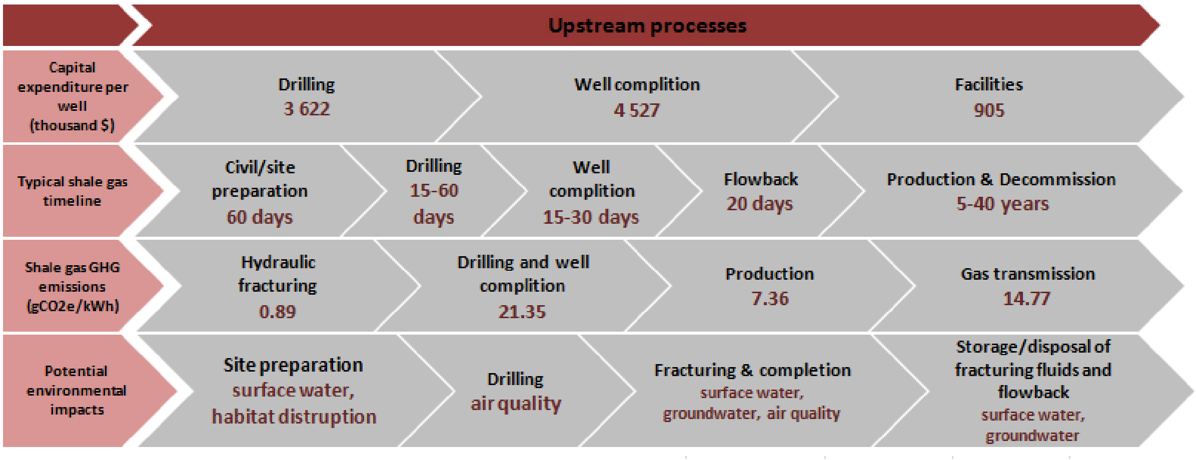

Figure 2 Diagram showing main factors related to shale gas upstream processes (adapted from Stark, 2012; Louwen, 2011; IHS, 2011 and Krupnick, 2013)

The average cost per shale gas well in the USA is around $9 million. Approximately 40% of this cost is associated with drilling, half with well completion (e.g. hydraulic fracturing and well casing) and the rest with other facilities such as material, fabrication and project management.

Typically it takes between 4 to 6 months before a shale gas well is prepared for production and then it can be producing for up to 40 years. Around 44g of CO_2 equivalent emissions per kWh are released during shale gas upstream processes. This is almost twice as much when compared to nuclear energy but about half when compared to coal (Louwen, 2011). Around half of these emissions are emitted during the drilling and well completion phase. This can bring to question the horizontal drilling and hydraulic fracturing method and its impact.

There are potentially significant environmental and health risks associated with each activity (Krupnick, 2013). When preparing the location, land has to be cleared and infrastructure put in place. Such actions can cause stormwater flows and habitat fragmentation and therefore have a negative impact on surface water and the local habitat. During drilling methane is venting and as a result polluting the air. Throughout the fracturing and well completion phase a significant volume of surface water and groundwater is used which can affect the level of freshwater (Krupnick, 2013). The flowback and fracturing fluids can also have significant environmental consequence if not handled safely and according to the best practice. Well completion as well as flowback storage and disposal can therefore also affect the level and quality of surface water and groundwater (Krupnick, 2013).

The key aspects of the upstream processes are emissions and flowbacks and fracturing fluids produced during the drilling and well completion phase and their potential environmental and health impacts.

2 Energy mix and context in Europe compared to the USA

Both in Europe and the USA, oil plays a major role in the energy mix accounting for around one third of the total primary energy consumption (Figure 3). Natural gas is the second most used source in both countries. However, while in Europe natural gas accounts for 25% of the total consumption, in the USA it is almost 30%. This difference is explained by the vast development of unconventional natural gas in the USA during the last ten years.

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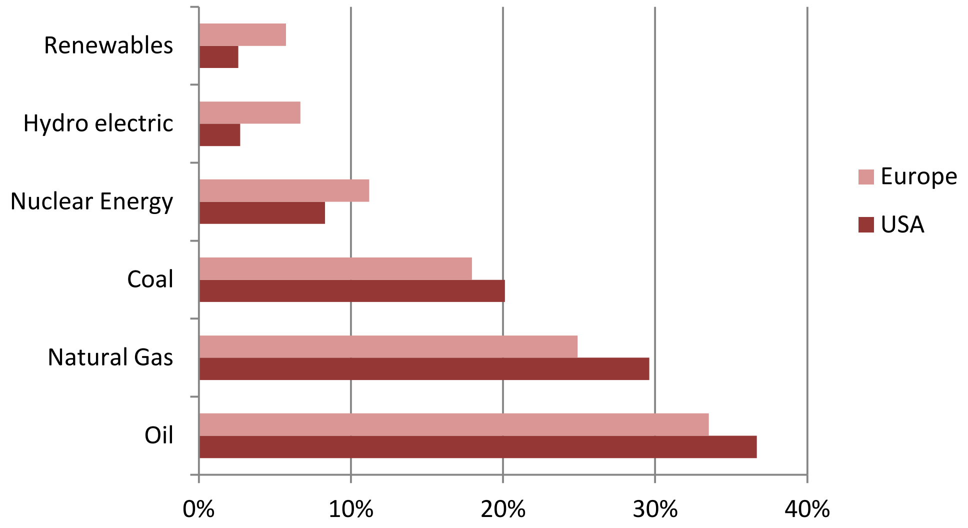

Figure 3 Primary energy consumption by energy source in Europe and USA in 2013 (source: BP, 2014)

Thirteen percent of the total consumption in Europe comes from renewable and hydroelectric energy which is twice as much compared to the USA. This is in line with the different approaches towards renewable and low carbon energies adopted by the EU and the USA. The EU set up the Renewable Energy Directive in 2009 which creates binding obligations for the members to supply the certain percentage of electricity from renewables (Elliott, 2013; EWEA, 2011). No such a directive exists in the USA (Elliott, 2013). The difference in energy policies between the EU and the USA perhaps started when the EU embraced the Kyoto protocol and included environmental protection in its Energy White Papers as one of its key pillars in 1997 (Evans, 2011). Although the USA also signed the Kyoto protocol in 1998, it never ratified the Treaty and therefore has no binding obligations (Evans, 2011).

In Europe, on the other hand, the renewable energies and GHG emission reduction targets are the key elements of its Energy policy (EU, 2014a). Not surprisingly, EU is also more successful in reducing its total emissions (Figure 4). The USA seems to be much more relaxed in this sense. For example, in 2005 hydraulic fracturing was excluded from the Environmental Protection

Agency´s Clean Water Act (although impact on water is one of the major concerns) and therefore many shale gas operations were able to proceed with little environmental impact assessment (Stevens, 2013).

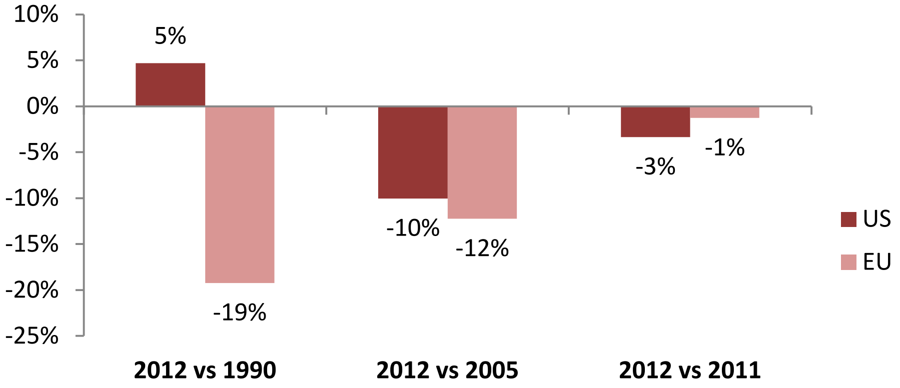

Figure 4 Change in GHG emissions (adapted from EPA, 2014 and EU, 2014b)

All this implies that EU energy policies are more environmentally oriented, while the U.S. energy policies are more economically based. This means that for shale gas to see significant future development, the EU has to be firstly convinced that shale gas is an environmentally sound energy source.

However, a strong environmental legislation is not the only factor that can be a barrier to future shale gas development in Europe. Table 1 shows some of these other factors. The most significant factor is a different geology. Shale gas in Europe was found in some cases at a deeper level than in the USA (Gusilov, 2012). This would most likely lead to higher extraction costs and the average cost per shale gas well in Europe would be higher than the $9 million claimed for the USA. Too complex and complicated permitting process and lack of gas infrastructure can also present big obstacles to further development.

Table 1 Different context in Europe compared to the USA (sources: Stevens, 2013; IoD, 2013; CRFB, 2013; Gusilov, 2012)

Area	USA	Europe
Geology	Many of the shale reserves have low clay content. Shale gas deposits are more often closer to the surface (3-4 km).	Higher clay content. Deposits deeper (5-6 km).
Research	The US government started funding the R&D into low permeable formations already in 1982- better know - how and skilled workforce.	Focus on shale gas only in the last few years.
Regulation	Energy Act from 1980 gave tax credits amounting to 50% per MMBTU. Intangible Drilling Cost Expensing Rule was also introduced which usually covered around 70% of costs of well development.	No such measurements. Planning and permitting system too complex and complicated.
Gas market & Infrastructure	Gas producers have some access to pipelines. Large and extensive gas pipelines.	Access by Third Party Access. In the UK grid connection delays had already negatively affected renewable industry.

3 Trade-offs

Even though there are potential risks associated with shale gas extraction there are also very significant potential economic benefits. For example, MacAvoy et al. (2012) calculated that the USA in 2011 was saving $103bn due to reduced price of natural gas. If the savings of not having to import the more expensive liquefied natural gas (LNG) were also included, the total amount saved would increase by additional $50bn a year. Although it is not very likely that shale gas development in Europe will have the same impact, the potential economic benefits are certainly not insignificant. A study of respected environmental consultancies suggests that the wholesale gas price could on average decrease between 6 to 14% in Europe depending on the level of the shale gas development (Williams and Summerton, 2013). That would bring annual savings between €12bn to €28bn. Cumulatively by 2050 Europe could see wholesale energy savings between €765bn to €1.7trillion (Williams and Summerton, 2013).

By 2050, it is estimated that between 0.6 and 1.1 million jobs would be created and between 1.7 and 3.8 trillion Euros would be added to the GDP (Williams and Summerton, 2013). One of the most significant benefits would however be the reduction in natural gas import dependency. Currently one third of the total EU gas imports come from Russia and half of this import goes through Ukraine (Euractiv, 2014). Although Europe would not become natural gas self-sufficient even with shale gas, it would certainly enhance its energy security through a decreased reliance on imports and diversifying its energy sources (ENDS, 2013; Economic Affairs Committee, 2014).

4 Methodology

The study was focused on analysing the environmental, economic and social aspects of using a particular energy source. In terms of environmental aspects the focus was mainly on parameters related to CO_2 and other emissions. The main focus of economic parameters was on employment creation and contributions to local and national wide economies. The key social parameters were focused on health impact.

The development of the sustainability indices of shale gas, conventional gas, coal and nuclear power was undertaken in six steps as follows.

4.1 Step 1: Selection and grouping of indicators

Scientific papers and other sources of information related to shale gas, conventional natural gas, coal and nuclear power were reviewed. Some of the values used in the analysis were used directly from these sources. However, due to the lack of information related to some indicators some values have been calculated or estimated to allow comparison across all energy sources. In some cases the estimations for shale gas were based on the values for conventional gas. Here the value for conventional gas was set as a baseline and the value for shale gas was determined by estimating how much this value could differ from conventional gas. Such a procedure was used for social indicators related to health. In some other cases it was assumed that the value for shale gas will be the same as for conventional gas. This assumption was for example used for indicators related to power plants. Some economic and environmental indicators related to nuclear power sector were also not available and had to be calculated (economic value added, water consumption and production cost).

Thanks to these calculations, estimations and values directly provided in scientific papers the analysis of 41 indicators was carried out. These indicators were divided into three main groups: environmental, economic and social as shown in Tables 4, 5 and 6, respectively.

4.2 Step 2: Judging the indicators

After grouping the indicators, each indicator was judged based on whether it had a positive or negative impact on overall sustainability index. For example, higher value of CO_2 emissions had a negative impact, while increase in employment had a positive impact on the sustainability index.

4.3 Step 3: Normalizing the indicators

The four sources of energy were qualitatively ranked against each other by normalising each indicator to unity. All indicators were normalized by expressing them on the scale from 0 to 1 where 1 represents the energy source with the most desirable value. In case of negative indicators this was performed by dividing the lowest value across all four energy sources with the individual indicator for each energy source. The normalization of positive indicators was performed by dividing each parameter with the highest value across all energy sources (Strezov et al., 2013). By using this method the best value (the highest for positive and the lowest for negative indicator) was assigned the number 1. Values for other energy sources were calculated proportionally to the best value. The closer the indicator to 1 the more desirable it is from the sustainability perspective.

4.4 Step 4: Weighting the indicators

To estimate the weights of each indicator the pair-wise comparison method was used (Krajnc and Glavic, 2005). The comparison was made between each pair of indicators by posing the question which of the two indicators was more important with respect to the overall sustainability. The intensity of preferences was expressed on a scale between 1 and 9 (see Table 2). This comparison method resulted in a N x N positive reciprocal matrix, where the diagonal aji=1 and reciprocal property aji= (1/aji), i,j= 1...n. To calculate the weight of each indicator, each column of the matrix was then normalised by dividing each indicator in the column by the sum of the column. The average of every row then represented the normalised weight for the particular indicator (Krajnc and Glavic, 2005).

Table 2 Comparison scale in pair-comparison method (Krajnc and Glavic, 2005)

Factor of preference	Importance definition
1	Equal importance
3	Moderate importance of one over another
5	Strong or essential importance of one over another
7	Very strong or demonstrated importance of one over another
9	Extreme importance of one over another
2,4,6,8	Intermediate values
Reciprocal, 1/p	Reciprocal for inverse comparison

4.5 Step 5: Calculating sub-indices

To calculate the sub-index the normalized value of each parameter was firstly multiplied by the respective weight of each parameter and then summed up as shown in Equation 1,

$$I_{\mathrm{S},jt} = \sum_{jit}^{n} W_{ji} \cdot I_{\mathrm{N},jit}^{+} + \sum_{jit}^{n} W_{ji} \cdot I_{\mathrm{N},jit}^{-}$$

Equation 1 Calculating sub-indices

$$\sum_{ji}^{n} W_{ji} = 1, \quad W_{ji} \geq 0$$

where IS, jt is the sustainability sub-index for a group of indicators j(environmental, j=1; economic, j=2; social, j=3) where t represents different energy sources (shale gas, t=1; conventional gas, t=2; coal, t=3; nuclear energy, t=4)

4.6 Step 6: Calculating the overall sustainability index

In the last step the tree sub-indices were combined to develop the overall sustainability index for each energy source. The sustainability index was calculated as shown in Equation 2,

$$I_{\mathrm{CSD},t} = \sum_{jt}^{n} W_j \cdot I_{\mathrm{S},jt}$$

Equation 2 Overall sustainability index

where WJ represents the relative importance of each sub-index (Krajnc and Glavic, 2005).

As a baseline, equal weights of one third (33%) were ascribed to each of the three sub-indices – this reflects that sustainability as a concept should give to all three aspects equal importance. The analysis however also looked how the overall sustainability index would change if more importance was given to one of the aspects. When calculating the overall index according to the Equation 2 higher weight of 50% was therefore given to one of the aspects and 25% to the other two as shown in table 3.

Table 3 Weights used for environmental, economic and social aspect of the sustainability index

	Environmental	Economic	Social
Baseline	1/3	1/3	1/3
Economic focus	25%	50%	25%
Environmental focus	50%	25%	25%
Social focus	25%	25%	50%

5 Results and Discussion

In the analysis 12 environmental, 17 economic and 12 social indicators were aggregated into one sustainability index comparing shale gas with other energy sources. Tables 4, 5 and 6 provide an overview of the grouped indicators with their normalized values (see appendix A for non-normalized values). Figures 5 shows the weights assigned to environmental, economic and social indicators.

Table 4 Environmental indicators with normalized values

Indicator		Shale gas	Conventional gas	Coal	Nuclear power	+/-	Source of information
Water consumption (l/kWh)	Extraction	0.0034	1.0000	0.0031	0.0003	-	Jenner and Lamadrid (2013); UCS (2011); NEI (2013)
	Processing	0.3621	0.3621	0.3820	1.0000	-	
	Transport	0.0035	0.0035	1.0000	1.0000	-	
	Combustion	1.0000	1.0000	0.4044	0.5432	-	
Emissions (gCO2e/kWh)	Upstream	0.5224	1.0000	0.2219	0.9549	-	Louwen (2011)
	Direct	0.0297	0.0297	0.0154	1.0000	-	
	Downstream	1.0000	1.0000	0.0050	0.0001	-	
Land use (m2/kwh)		1.0000	0.1000	0.0750	0.6000	-	Evans et al. (n.a.); Jenner and Lamadrid (2013)
Ozone layer depletion (µg CFC-11 eq./kWh)		0.0800	0.0800	0.2500	1.0000	-	Azapagic (2011)
Other emissions (g/MJ)	NOx	0.0021	0.0008	0.0002	1.0000	-	Ecoinvent (2009); Litovitz (2013); Jenner and Lamadrid (2013)
	$PM_{2.5}$	0.0059	0.0006	0.0000	1.0000	-	
	SO_2	0.0009	0.0015	0.0000	1.0000	-	

Table 5 Economic indicators with normalized values

Indicator		**Shale gas**	**Conventional gas**	**Coal**	**Nuclear power**	**+/-**	**Source of information**
Cost per GJ of energy ($)		0.0000	0.0000	0.0000	1.0000	-	IEA (2010b); Erismann (2011)
Value added contribution (million $)	Direct	0.2736	1.0000	0.2174	0.1633	+	NMA (2013); IHS (2011)
	Indirect and Induced	0.3340	1.0000	0.2822	0.2292	+	
Dependence on imports in Europe (%) (import/total consumption)		0.6119	0.6119	1.0000	0.4316	-	EU (2012); FORATOM (2014)
Fuel price sensitivity (%) - ratio of the fuel cost to the electricity generation cost		0.1370	0.1370	0.2857	1.0000	-	IEA (2010a)
Power Plant	Power plant construction time	1.0000	1.0000	0.7500	0.5000	-	NETL (2007); Voß (2006); Evans et al. (n.a.); Stamford and Azapagic (2011)
	Power plant lifespan	0.7000	0.7000	0.7000	1.0000	+	
	Power plant efficiency (%)	1.0000	1.0000	0.7857	0.6735	+	
	Power plant capacity factor (%)	0.5161	0.5161	0.6626	1.0000	+	
The lifetime of fuel reserves		0.5721	0.5110	1.0000	0.9174	+	BP (2013); Stamford and Azapagic (2011)
Fuel storage capacity (GJ/m^3)		0.0000	0.0000	0.0000	1.0000	+	Stamford and Azapagic (2011)
Overnight Capital Cost of Power Plant($/kW)		1.0000	1.0000	0.4828	0.3855	-	EIA (2013b)
Fixed O&M Cost ($/kW-yr)		1.0000	1.0000	0.2166	0.1335	-	
Variable O&M Cost (cents $/kWh)		0.1557	0.1557	0.2946	1.0000	-	
Total life cycle raw material requirements	Iron (kg/GWh)	0.3688	0.3688	0.2688	1.0000	-	Voß (2006)
	Copper (kg/GWh)	1.0000	1.0000	0.1250	0.1667	-	
	Bauxite (kg/GWh)	1.0000	1.0000	0.0667	0.0741	-	

Table 6 Social indicators with normalized values

Indicator		Shale gas	Conventional gas	Coal	Nuclear power	+/-	Source of information
Employment		0.3183	1.0000	0.3289	0.0853	+	NMA (2013); IHS (2011)
Average annual salary ($ per year)		1.0000	0.8279	0.9051	0.9323	+	
Cost of eliminating entirely the safety risks from different electricity options (£/ GWh/yr)		0.1375	0.1375	0.0011	1.0000	-	Azapagic et al. (2011)
Death from accidents (deaths per TWh)	among the public	0.1364	0.1500	0.1500	1.0000	-	Markandya and Wilkinson (2007)
	occupational	0.9091	1.0000	0.0100	0.0526	-	
Air pollution related effects	deaths (deaths/TWh)	0.0139	0.0186	0.0021	1.0000	-	
	serious illness (cases/TWh)	0.0055	0.0073	0.0010	1.0000	-	
	minor illness (cases/TWh)	0.0000	0.0000	0.0000	1.0000	-	
Average jobs per MW installed over the lifetime of the plant		0.0714	0.0714	0.6429	1.0000	+	Wei et al. (2010)
Total person-yrs/GWh		0.2000	0.2000	0.6000	1.0000	+	
Human health risk (Years of Life Lost (YOLL)/ Twh)	from power plant emissions	0.0000	0.0000	0.0000	1.0000	-	Voß (2006)
	from up and downstream processes	0.2609	0.3478	0.4000	1.0000	-	

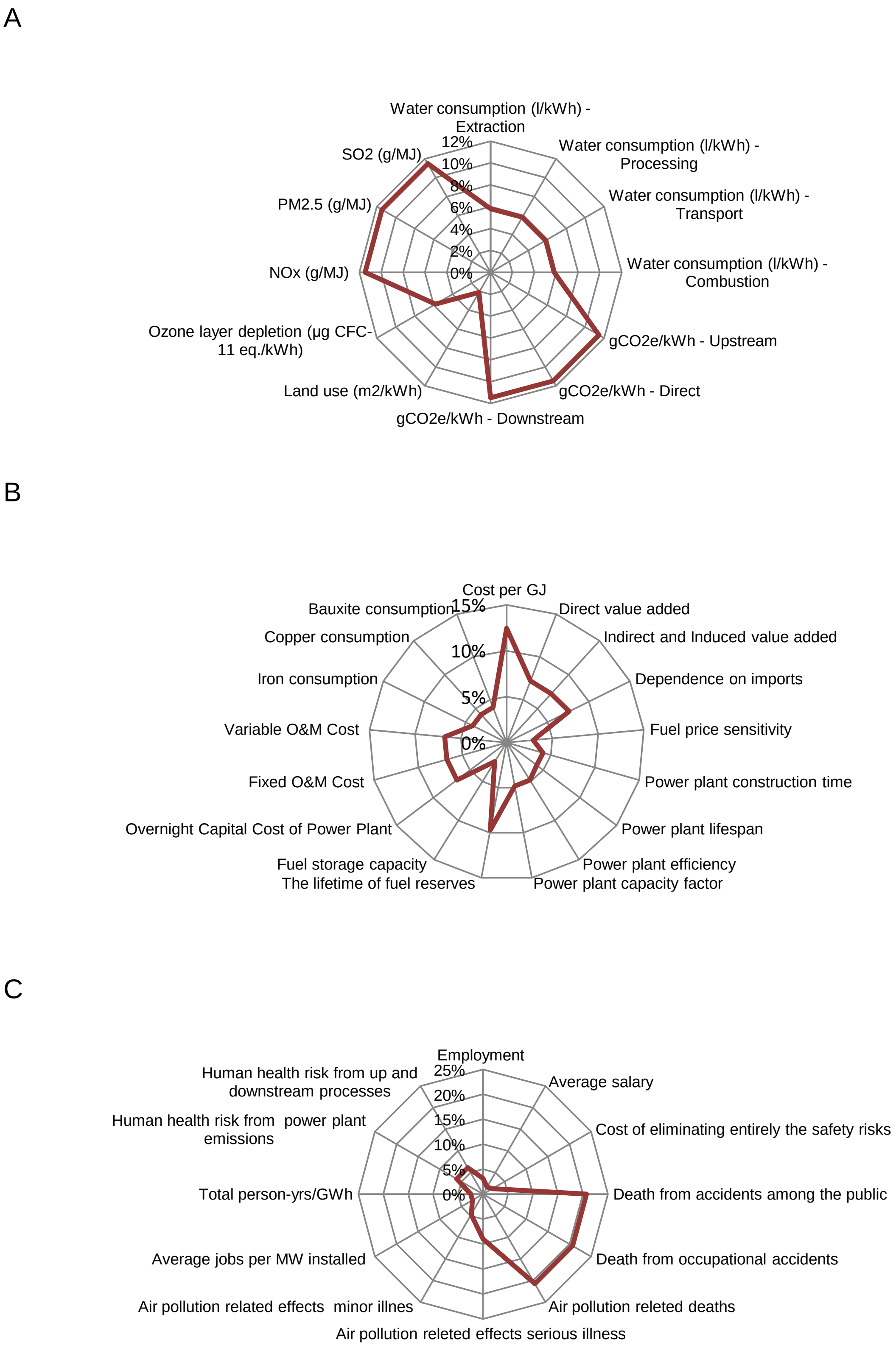

Figure 5 Weights of environmental (A), economic (B) and social (C) indicators

Using the pair-wise comparison method enabled to determine which of the indicators were the most important within the group. In terms of environmental aspect the highest weights were assigned to indicators related to CO_2 and other emissions (NOx, PM2,5 and SOx) as the most representative indicators of environmental impact (see Figure 5 above). Regarding the economic aspect, the highest weights were given to indicators related directly to cost of fuel production and to energy security (dependence on imports and the lifetime of the fuel reserves). With respect to the social group, the highest weights were assigned to indicators of death both from accidents and air pollution as they represent the most severe social impact.

By multiplying the weights shown in Figure 5 with normalized values the sustainability sub-indices were calculated (Figure 6). Nuclear energy shows the highest results both for environmental and social sub-index scoring almost 0.8 point (the closer to 1 the more sustainable) which highly exceeds the values for other energy sources. The values for conventional natural gas as the second best option are only half of the values gained by nuclear energy (0.38 for environmental and 0.32 for social sub-index). Shale gas shows lower values then conventional natural gas – 0.28 and 0.27 respectively. Both environmental and social sub-index for coal is more than 5 times lower than for nuclear energy.

With respect to the economic aspect the difference between the best and worst energy option is significantly lower than for the other two aspects. This means that the economic impact of all energy sources is more similar than their environmental or social impact. Conventional natural gas is in this case the best option followed very closely by nuclear energy (0.63 and 0.62 respectively). Shale gas ranks again as the third best option (0.54) and coal as the worst one (0.43).

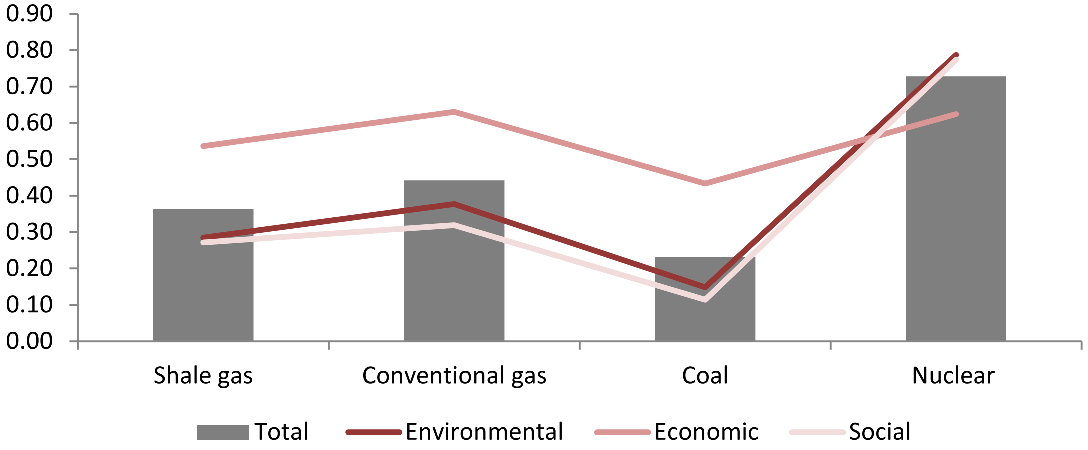

Figure 6 Sub-indices and the total index when all groups are given the equal weights

The overall sustainability index (when each group of indicators is given an equal weight) shows that nuclear energy is the best option (0.73) followed by conventional natural gas (0.44), shale gas (0.36) and coal (0.23). The key indicators making shale gas less sustainable than conventional natural gas and nuclear energy are emissions released during the upstream processes and illnesses/deaths from accidents and air pollution.

The analysis also looked how the overall sustainability index would change if the weights assigned to each group of indicators were not equal. If environmental group of indicators was given greater importance (50% of the total weights rather than 33%) the overall index for shale gas, conventional gas and coal would decrease while it would increase for nuclear power compared to the baseline (Figure 7). The same situation happens when higher importance is put on the social aspect. If however, the greater importance is given to the economic aspect, the opposite output is seen – decrease in sustainability index for nuclear energy and increase for all other energy types compared to baseline. This shows that the main advantage of nuclear energy over other sources is in environmental and social parameters. Therefore if more importance is put on these parameters the bigger is the difference between nuclear energy and other sources and the more desirable nuclear energy becomes. When economic indicators are given more importance the difference between nuclear and other energy sources decreases.

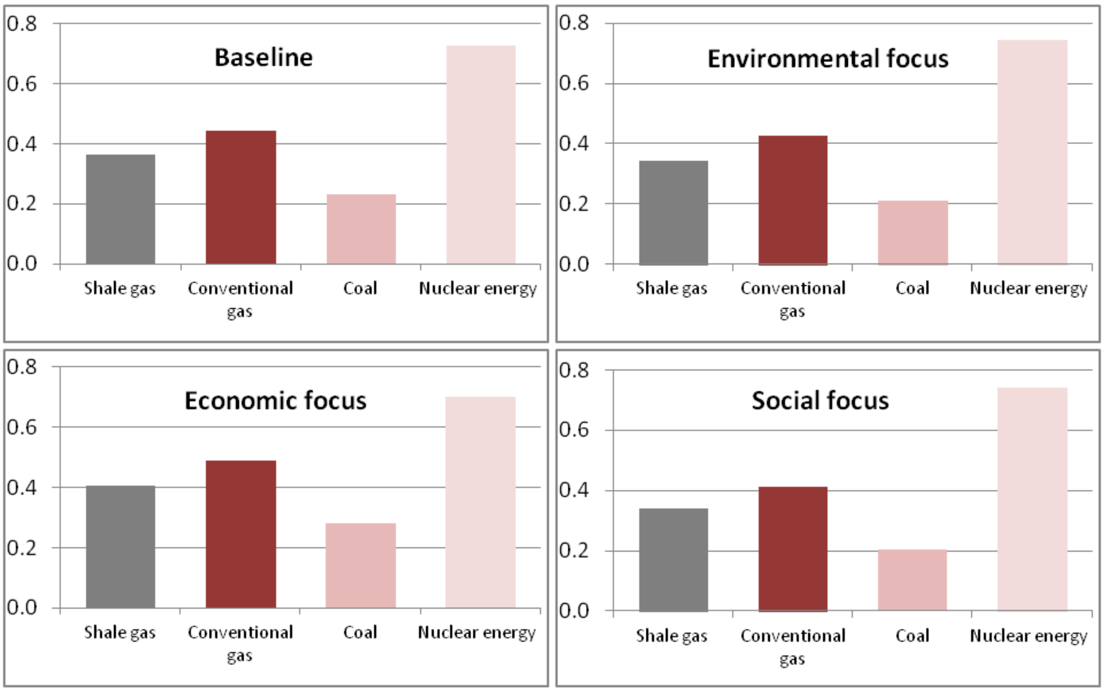

Figure 7 Comparison of the different scenarios

Nevertheless, even if 50% weight is ascribed to economic indicators and only 25% to environmental and social indicators nuclear energy is still by a significant margin the most sustainable energy source (see Figure 7).

In all three different situations the value of sustainability index of shale gas ranks as the third best – about half of nuclear energy, about 20% lower than conventional natural gas and more than 50% higher than coal. The analysis shows that no matter which of the three aspects is given greater importance shale gas is always a preferable option to coal. Replacing coal with shale gas in Europe will reduce the total emissions and would be in line with the EU´s energy policy.

There are however few limitations related to this analysis that could alter the overall output. The lack of data, especially for shale gas, meant that some of the values had to be estimated based on the available information (in some cases qualitative rather than quantitative). Estimation values used in this analysis could be underestimating or overestimating the true impact of shale gas.

Even though this paper aims to evaluate impact in Europe, due to lack of data some values used were related to the shale gas development in the USA. The situation in Europe might be different and that could alter the study findings.

Although the pair-wise comparison is a sound method, as it provides a sensitive perception to make a distinction which of the two indicators is more important, it is still exposed to high level of subjectivity.

The selection of the parameters is also subjective. Other studies might select indicators which were not included in this study and get different outputs.

All these important points should be taken into consideration when looking at the results of the analysis.

Nevertheless, the results of the analysis are in line with other studies (e.g. Grubert and Kitasei, 2010; Mielke et al., 2010; Wang et al., 2014; Fulton, 2011; Weisser, 2007). These studies found that shale gas or natural gas is in their particular area of examination (e.g. GHG emissions or water consumption) a better alternative than coal. This concurs with the outcomes of this study. It was also found that it is beneficial from the sustainability perspective to use more shale gas and less coal which is in accordance with Jenner and Lamadrid (2013) or Moniz et al. (2011). Other sources (NASA, 2013; Azapagic et al. 2011; Sims et al. 2003) point out the advantage (especially environmental and social) of nuclear energy over other energy sources and that also corresponds with the results. In this sense the outcome of the study is not very surprising and shows a reasonable level of soundness and reliability. It brings more insights into the potential impact of shale gas. Furthermore, it provides the analysis with a more comprehensive viewpoint of sustainability as more indicators are taken into consideration. Other research studies seem to be more narrowly focussed.

6 Conclusion

The analysis indicates that shale gas is less desirable from the sustainability perspective than nuclear energy or conventional gas. The sustainability index of shale gas compared to conventional gas shows lower value due to the higher emissions and associated health risks in the upstream phase. Shale gas nevertheless shows much less negative environmental and social impact than coal. It would be advisable for Europe to reduce the usage of coal and use natural gas instead. As renewable energies are currently expensive compared to other energy sources shale gas could serve as transition fuel to an age of renewable energies.

However, before Europe could see a significant development in shale gas many actions have to take place. The development of shale gas in Europe cannot be left to the market. Governments have to send positive signals otherwise the uncertainly about the future development will deter the potential investors. There are many barriers associated with shale gas and policies must be deployed to overcome some of these barriers. Governments have to invest in further research and development as further exploration and appraisal of the shale gas resources have to be carried out.

The increasing uncertainty in EU´s energy supplies and consequently security issues are making EU to look at shale gas as the potential solution. Shale gas would not only reduce EU import dependency but could also have huge impact in terms of job creation, GDP contribution, lower energy prices and consequently the overall competitiveness of the European region.

Nevertheless, there is a great need for further research. The currently available studies have not been researching some of the related topics enough to fully comprehend the full impact. Further examination of the environmental risks is certainly needed. Another very important area is to better understand the impact of shale gas on communities. One of the essential steps is to figure out how to maximise the benefits and reduce the negatives for communities and therefore make shale gas development sustainable and socially acceptable within these communities. More thorough research has to be conducted to also analyse the health and welfare effects of water and air pollution. Additional research has to be undertaken regarding increased truck traffic and its consequences, such as traffic accidents and congestion. In addition, the scientific research should also cover the impact of shale gas infrastructure on habitat fragmentation.

Even though the potential value of shale gas is huge, due to the many barriers mentioned it cannot be assumed that shale gas will play any significant role in the European energy mix within this decade. Although shale gas in the USA showed a rapid boom after 2008 the whole industry did not appear overnight, as the first investments into R&D had occurred already in 1980s. There is no reason to think that development in Europe could progress any faster. Therefore it is unlikely to see significant shale production in Europe earlier than by the middle of the next decade. But to reach that point, an extensive research will have to be carried out to fully understand the true impact of shale gas and full political and public support will be needed.

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APPENDICES

Appendix A Non-normalized value of each indicator

Table A 1 Values of environmental indicators

Environmental indicators		Symbol	Shale gas	Conventional gas	Coal	Nuclear energy
Water consumption (l/kWh)	Extraction	WCE	0.029	0.000	0.032	0.367
	Processing	WCP	0.058	0.058	0.055	0.021
	Transport	WCT	0.029	0.029	0.000	0
	Combustion	WCC	1.195	1.195	2.955	2.2
Emission per kWh (gCO2e)	Upstream (mining, extraction, processing, transportation and construction of all facilities)	EU	44.6	23.3	105	24.4
	Direct (power plant operation, combustion)	ED	462	462	892	13.7
	Downstream (decommissioning of all installations, waste treatment and disposal, including infrastructure)	Edo	0	0	0.02	1.1
Land use (m2/kwh)		LU	0.00003	0.0003	0.0004	0.00005
Ozone layer depletion ((µg CFC-11 eq./kWh)		OZ	12.5	12.5	4	1
Other emissions (kg/GJ or g/MJ)	NOx	NO	1.53E-02	4.00E-02	1.96E-01	3.24E-05
	$PM_{2.5}$	PM	2.84E-04	3.00E-03	1.18E+00	1.68E-06
	SO_2	SO	5.02E-04	3.00E-04	2.40E-01	4.38E-07

Table A 2 Values of economic indicators

Economic indicators		Symbol	Shale gas	Conventional gas	Coal	Nuclear energy
Cost per GJ of energy (dollars in the USA)		CO	5.03773585	3.1	0.58	0.000486486
Value added contribution in the USA (contribution to GDP in million of dollars)	Direct	VAD	47063	172000	37400	28086
	Indirect and Induced	VAID	71151	213000	60100	48829
Dependence on imports (Europe) (%) (import/total consumption)		DI	67	67	41	95
Ratio of the fuel cost to the generation cost (fraction) (%)		CV	73	73	35	10
Power Plant	Power plant construction time	CT	3	3	4	6
	Power plant lifespan	LS	35	35	35	50
	Power plant efficiency	PE	49	49	38.5	33
	Power plant capacity factor (%)	CF	46.5	46.5	59.7	90.1
The lifetime of fuel reserves		LFL	62.4	55.7	109	100
Fuel storage capacity (GJ/m^3)		FSC	0.035	0.035	21	10,000,000
Overnight Capital Cost of Power Plant($/kW)		CC	2132	2132	4416.29	5530
Fixed O&M Cost ($/kW-yr)		FC	12.45	12.45	57.49	93.28
Variable O&M Cost (cents $/kWh)		VC	1.3745	1.3745	0.7264	0.214
Total life cycle raw material requirements	Iron (kg/GWh)	IR	1239	1239	1700	457
	Copper (kg/GWh)	COP	1	1	8	6
	Bauxite (kg/GWh)	BA	2	2	30	27

Table A 3 Values of social indicators

Social indicators		**Symbol**	**Shale gas**	**Conventional gas**	**Coal**	**Nuclear energy**
Employment		EM	197,999	622,000	204,580	53,082
Average annual salary (dollars per year)		AS	90,000	74,512	81,462	83,910
Cost of eliminating entirely the safety risks from different electricity options (pounds/ GWh/yr)		CE	4,000,000	4,000,000	500,000,000	550,000
Death from accidents - among the public (deaths per TWh)		PD	0.0220	0.0200	0.0200	0.0030
Death from accidents - occupational (deaths/TWh)		OD	0.0011	0.0010	0.1000	0.0190
Air pollution - related effects - deaths (deaths/TWh)		DA	3.73	2.80	24.50	0.05
Air pollution - related effects - serious illness (cases/TWh)		IA	40.00	30.00	225.00	0.22
Air pollution - related effects - minor illness (cases/TWh)		iA	937.33	703.00	13,288.00	0.00
Average jobs per MW installed over the lifetime of the plant	construction, installation and manufacturing	JMW	0.03	0.03	0.27	0.42
Total person-yrs/GWh	construction, installation and manufacturing	PY	0.01	0.01	0.03	0.05
Human health risk (Years of Life Lost (YOLL)/ Twh)	from power plant emissions	HHR	14.00	14.00	62.50	0.00
	from up and downstream processes	HHRa	30.67	23.00	20.00	8.00

Appendix B Calculated weights of each indicator using pair-wise comparison method

Table B 1 Relative weights of environmental indicators

Indicator	WCE	WCP	WCT	WCC	EU	ED	Edo	LU	OZ	NO	PM	SO	
WCE	1.00	1.00	1.00	1.00	0.50	0.50	0.50	3.00	1.00	0.50	0.50	0.50	
WCP	1.00	1.00	1.00	1.00	0.50	0.50	0.50	3.00	1.00	0.50	0.50	0.50	
WCT	1.00	1.00	1.00	1.00	0.50	0.50	0.50	3.00	1.00	0.50	0.50	0.50	
WCC	1.00	1.00	1.00	1.00	0.50	0.50	0.50	3.00	1.00	0.50	0.50	0.50	
EU	2.00	2.00	2.00	2.00	1.00	1.00	1.00	5.00	2.00	1.00	1.00	1.00	
ED	2.00	2.00	2.00	2.00	1.00	1.00	1.00	5.00	2.00	1.00	1.00	1.00	
Edo	2.00	2.00	2.00	2.00	1.00	1.00	1.00	5.00	2.00	1.00	1.00	1.00	
LU	0.33	0.33	0.33	0.33	0.20	0.20	0.20	1.00	0.33	0.20	0.20	0.20	
OZ	1.00	1.00	1.00	1.00	0.50	0.50	0.50	3.00	1.00	0.50	0.50	0.50	
NO	2.00	2.00	2.00	2.00	1.00	1.00	1.00	5.00	2.00	1.00	1.00	1.00	
PM	2.00	2.00	2.00	2.00	1.00	1.00	1.00	5.00	2.00	1.00	1.00	1.00	
SO	2.00	2.00	2.00	2.00	1.00	1.00	1.00	5.00	2.00	1.00	1.00	1.00	
SUM	17.33	17.33	17.33	17.33	8.70	8.70	8.70	46.00	17.33	8.70	8.70	8.70	**Weights**
WCE	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.06	**6%**
WCP	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.06	**6%**
WCT	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.06	**6%**
WCC	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.06	**6%**
EU	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	**11%**
ED	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	**11%**
Edo	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	**11%**

LU	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	**2%**
OZ	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.06	**6%**
NO	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	**11%**
PM	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	**11%**
SO	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.12	0.11	0.11	0.11	**11%**

Table B 2 Relative weights of economic indicators

Indicator	**CO**	**VAD**	**VAID**	**DI**	**CV**	**CT**	**LS**	**PE**	**CF**	**LFL**	**FSC**	**CC**	**FC**	**VC**	**IR**	**COP**	**BA**	
CO	1.00	2.00	2.00	2.00	3.00	3.00	3.00	2.00	2.00	2.00	4.00	2.00	2.00	2.00	3.00	3.00	3.00	
VAD	0.50	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	0.50	2.00	1.00	1.00	1.00	2.00	2.00	2.00	
VAID	0.50	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	0.50	2.00	1.00	1.00	1.00	2.00	2.00	2.00	
DI	0.50	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	1.00	3.00	1.00	1.00	1.00	2.00	2.00	2.00	
CV	0.33	0.50	0.50	0.50	1.00	0.50	0.50	0.50	0.50	0.50	1.00	0.50	0.50	0.50	0.50	0.50	0.50	
CT	0.33	0.50	0.50	0.50	2.00	1.00	1.00	1.00	1.00	0.50	2.00	0.50	0.50	0.50	1.00	1.00	1.00	
LS	0.33	0.50	0.50	0.50	2.00	1.00	1.00	1.00	1.00	0.50	2.00	0.50	0.50	0.50	1.00	1.00	1.00	
PE	0.50	0.50	0.50	0.50	2.00	1.00	1.00	1.00	1.00	0.50	2.00	1.00	1.00	1.00	1.00	1.00	1.00	
CF	0.50	0.50	0.50	0.50	2.00	1.00	1.00	1.00	1.00	0.50	2.00	1.00	1.00	1.00	1.00	1.00	1.00	
LFL	0.50	2.00	2.00	1.00	2.00	2.00	2.00	2.00	2.00	1.00	4.00	2.00	2.00	2.00	2.00	2.00	2.00	
FSC	0.25	0.50	0.50	0.33	1.00	0.50	0.50	0.50	0.50	0.25	1.00	0.33	0.33	0.33	0.50	0.50	0.50	
CC	0.50	1.00	1.00	1.00	2.00	2.00	2.00	1.00	1.00	0.50	3.00	1.00	1.00	1.00	2.00	2.00	2.00	
FC	0.50	1.00	1.00	1.00	2.00	2.00	2.00	1.00	1.00	0.50	3.00	1.00	1.00	1.00	2.00	2.00	2.00	
VC	0.50	1.00	1.00	1.00	2.00	2.00	2.00	1.00	1.00	0.50	3.00	1.00	1.00	1.00	2.00	2.00	2.00	
IR	0.33	0.50	0.50	0.50	2.00	1.00	1.00	1.00	1.00	0.50	2.00	0.50	0.50	0.50	1.00	1.00	1.00	
COP	0.33	0.50	0.50	0.50	2.00	1.00	1.00	1.00	1.00	0.50	2.00	0.50	0.50	0.50	1.00	1.00	1.00	
BA	0.33	0.50	0.50	0.50	2.00	1.00	1.00	1.00	1.00	0.50	2.00	0.50	0.50	0.50	1.00	1.00	1.00	
SUM	7.75	14.50	14.50	13.33	33.00	25.00	25.00	21.00	21.00	10.75	40.00	15.33	15.33	15.33	25.00	25.00	25.00	**Weights**
CO	0.13	0.14	0.14	0.15	0.09	0.12	0.12	0.10	0.10	0.19	0.10	0.13	0.13	0.13	0.12	0.12	0.12	**12%**
VAD	0.06	0.07	0.07	0.08	0.06	0.08	0.08	0.10	0.10	0.05	0.05	0.07	0.07	0.07	0.08	0.08	0.08	**7%**
VAID	0.06	0.07	0.07	0.08	0.06	0.08	0.08	0.10	0.10	0.05	0.05	0.07	0.07	0.07	0.08	0.08	0.08	**7%**
DI	0.06	0.07	0.07	0.08	0.06	0.08	0.08	0.10	0.10	0.09	0.08	0.07	0.07	0.07	0.08	0.08	0.08	**8%**
CV	0.04	0.03	0.03	0.04	0.03	0.02	0.02	0.02	0.02	0.05	0.03	0.03	0.03	0.03	0.02	0.02	0.02	**3%**
CT	0.04	0.03	0.03	0.04	0.06	0.04	0.04	0.05	0.05	0.05	0.05	0.03	0.03	0.03	0.04	0.04	0.04	**4%**
LS	0.04	0.03	0.03	0.04	0.06	0.04	0.04	0.05	0.05	0.05	0.05	0.03	0.03	0.03	0.04	0.04	0.04	**4%**

PE	0.06	0.03	0.03	0.04	0.06	0.04	0.04	0.05	0.05	0.05	0.05	0.07	0.07	0.07	0.04	0.04	0.04	**5%**
CF	0.06	0.03	0.03	0.04	0.06	0.04	0.04	0.05	0.05	0.05	0.05	0.07	0.07	0.07	0.04	0.04	0.04	**5%**
LFL	0.06	0.14	0.14	0.08	0.06	0.08	0.08	0.10	0.10	0.09	0.10	0.13	0.13	0.13	0.08	0.08	0.08	**10%**
FSC	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	**2%**
CC	0.06	0.07	0.07	0.08	0.06	0.08	0.08	0.05	0.05	0.05	0.08	0.07	0.07	0.07	0.08	0.08	0.08	**7%**
FC	0.06	0.07	0.07	0.08	0.06	0.08	0.08	0.05	0.05	0.05	0.08	0.07	0.07	0.07	0.08	0.08	0.08	**7%**
VC	0.06	0.07	0.07	0.08	0.06	0.08	0.08	0.05	0.05	0.05	0.08	0.07	0.07	0.07	0.08	0.08	0.08	**7%**
IR	0.04	0.03	0.03	0.04	0.06	0.04	0.04	0.05	0.05	0.05	0.05	0.03	0.03	0.03	0.04	0.04	0.04	**4%**
COP	0.04	0.03	0.03	0.04	0.06	0.04	0.04	0.05	0.05	0.05	0.05	0.03	0.03	0.03	0.04	0.04	0.04	**4%**
BA	0.04	0.03	0.03	0.04	0.06	0.04	0.04	0.05	0.05	0.05	0.05	0.03	0.03	0.03	0.04	0.04	0.04	**4%**

Table B 3 Relative weights of social indicators

Indicator	**EM**	**AS**	**CE**	**PD**	**OD**	**DA**	**IA**	**iA**	**JMW**	**PY**	**HHR**	**HHRa**	
EM	1.00	2.00	2.00	0.14	0.14	0.14	0.33	0.50	2.00	2.00	0.33	0.33	
AS	0.50	1.00	0.50	0.11	0.11	0.11	0.20	0.25	0.50	0.50	0.25	0.25	
CE	0.50	2.00	1.00	0.11	0.11	0.11	0.20	0.33	1.00	1.00	0.33	0.33	
PD	7.00	9.00	9.00	1.00	1.00	1.00	3.00	7.00	9.00	9.00	3.00	3.00	
OD	7.00	9.00	9.00	1.00	1.00	1.00	3.00	7.00	9.00	9.00	3.00	3.00	
DA	7.00	9.00	9.00	1.00	1.00	1.00	3.00	7.00	9.00	9.00	3.00	3.00	
IA	3.00	5.00	5.00	0.33	0.33	0.33	1.00	3.00	3.00	3.00	2.00	2.00	
iA	2.00	4.00	3.00	0.14	0.14	0.14	0.33	1.00	2.00	2.00	1.00	1.00	
JMW	0.50	2.00	1.00	0.11	0.11	0.11	0.33	0.50	1.00	1.00	0.50	0.50	
PY	0.50	2.00	1.00	0.11	0.11	0.11	0.33	0.50	1.00	1.00	0.50	0.50	
HHR	3.00	4.00	3.00	0.33	0.33	0.33	0.50	1.00	2.00	2.00	1.00	1.00	
HHRa	3.00	4.00	3.00	0.33	0.33	0.33	0.50	1.00	2.00	2.00	1.00	1.00	
Sum	35.00	53.00	46.50	4.73	4.73	4.73	12.73	29.08	41.50	41.50	15.92	15.92	**Weights**
EM	0.03	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.05	0.05	0.02	0.02	**3%**
AS	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	**2%**

CE	0.01	0.04	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	**2%**
PD	0.20	0.17	0.19	0.21	0.21	0.21	0.24	0.24	0.22	0.22	0.19	0.19	**21%**
OD	0.20	0.17	0.19	0.21	0.21	0.21	0.24	0.24	0.22	0.22	0.19	0.19	**21%**
DA	0.20	0.17	0.19	0.21	0.21	0.21	0.24	0.24	0.22	0.22	0.19	0.19	**21%**
IA	0.09	0.09	0.11	0.07	0.07	0.07	0.08	0.10	0.07	0.07	0.13	0.13	**9%**
iA	0.06	0.08	0.06	0.03	0.03	0.03	0.03	0.03	0.05	0.05	0.06	0.06	**5%**
JMW	0.01	0.04	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.03	**2%**
PY	0.01	0.04	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.03	**2%**
HHR	0.09	0.08	0.06	0.07	0.07	0.07	0.04	0.03	0.05	0.05	0.06	0.06	**6%**
HHRa	0.09	0.08	0.06	0.07	0.07	0.07	0.04	0.03	0.05	0.05	0.06	0.06	**6%**