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CRANFIELD UNIVERSITY

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UK Shale Gas and Its Role in the UK’s Natural Gas Mix

SCHOOL OF APPLIED SCIENCES
Environmental Management for Business

MSc Thesis
Academic Year: 2012 - 2013

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

ABSTRACT

It has been suggested by recent research that immense reservoirs of shale gas can be found deep beneath the UK. Their exact extent is jet to be determined but several studies suggest that its amount could be as high as 566 cubic kilometers (20 trillion cubic feet) of technically recoverable shale gas.

The aim of this study is to determine how much of natural gas is the UK going to need in the future, whether there is a room for the shale gas in the UK's natural gas mix and if so, whether it is reasonable for the UK to employ its indigenous shale gas rather than import LNG from the carbon and economic perspective, since the latter one is considered as more polluting.

Approach this study has chosen is to first determine amounts of natural gas the UK is going to need until the year 2030 by carrying an analysis of the UK's electricity generation sector and the role of natural gas in it, combined with the broader natural gas demand. After estimation of total amounts of natural gas needed, analysis of the UK's natural gas mix compositions has been carried. Gap between overall natural gas demand and supplying capabilities of the UK's conventional production and pipeline imports has been identified. The identified gap can be filled by either LNG imports or the UK indigenous shale gas. Emission factors of each natural gas source have been used and future prices of the EUA and the price of the very gas itself have been estimated to carry the final economic analysis.

Results of this study suggest that use of shale gas instead of LNG would lead to savings of 8 to 32 million tons of CO_2e, which translates into anything between £124 and £510 million by the year 2030. Furthermore, analyses of the time period 2005 – 2013 suggsts that if the UK's shale gas has been used instead of LNG in the past, this would have led to carbon savings of 5 million tons of CO_2e and subsequent monetary savings of £55 million expressed in the EUA permits only.

KEYWORKDS

Shale gas/ conventional production/ carbon footprint/ forecast/ environment/ efficiency/ emissions/ price/ LNG/ import/ CO_2 /energy/ electricity/ ecology/ extraction

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LNG	liquefied Natural Gas
LCPD	Large Combustion Plant Directive
IED	Industrial Emissions Directive
UKERC	UK Energy Research Center
GHG	Greenhouse gas
UK	United Kingdom
EU	European Union
EUA	EU emission allowance
EU ETS	European Union Emission Trading Scheme
CCS	Carbon Capture and Storage
UKERC	UK Energy Research Center
CO_2e	Carbon Dioxide equivalent

This thesis has been designed in compliance with the requirements for scientific papers published in the journal Environmental Science & Technology.

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INTRODUCTION

Recent research suggests that large quantities of natural gas can be found deep beneath the UK, trapped in the shale formations. Even conservative estimates go as high as 566 km^3 (20 trillion cubic feet) of technically recoverable shale gas (The Royal Society, 2012; British Geological Survey, 2013), which could keep the UK self-sufficient for decades.

Sharp decrease in the UK's conventional production (Department of Energy & Climate Change, 2012) has led to revisiting of the indigenous shale gas question as an alternative to the rapidly growing imports of natural gas from abroad. The aim of this study was to determine whether there is a room for the UK indigenous shale gas in the UK's natural gas mix by carrying an analysis of the UK's electricity generation sector and role of natural gas in it, in order to estimate future natural gas demand for electricity generation. Amount of natural gas necessary for electricity generation together with broader natural gas demand form the UK's overall natural gas demand. Further, four major ways of sourcing of natural gas (indigenous conventional production, pipeline imports, indigenous shale gas and LNG imports) were examined and compared on based of their carbon footprint in order to determine the composition of the UK's future natural gas mix. As the aim of this study was not to evaluate possible contributions of the UK's indigenous shale gas merely from the carbon perspective but as well from the economic perspective, future European Emission Allowance (EUA) prices and future natural gas prices were estimated to lay the bases for the final economic analyses.

Analysis of the UK's fuel input into electricity generation mix provides evidence that the UK is going to face a power shortage in the years to come. Directives such as Large Combustion Plant Directive (LCPD) and Industrial Emission Directive (IED) (Defra, 2010) will inevitably lead to closing of the large coal fired power-plants. Majority of UK's nuclear power-plants are at the end of their predicted lifespan and new are just in the phase of planning or proposal (World Nuclear Association, 2013). Even though growing substantially in the past decade or so, renewable sources of energy are not growing fast enough to fill the gap between decreasing supply, and stable, or even slightly growing UK's electricity demand (Department of energy & climate change, 2012b). This together with steadily decreasing, but still substantial broader natural gas demand puts pressure on the UK's natural gas supply. Results provided by above described analyses are in consensus with the research presented by Stevens. P., (2012). Growing pipeline imports still cannot keep up with the sharply decreasing UK's conventional production which opens gap between the UK's natural gas demand and supply. This gap can be filled be either LNG imports or the UK shale gas, when the latter one is considered as less polluting. (Cranfield University, 2013; Jiang et al., 2011).

LITERATURE REVIEW / BACKGROUND

About shale gas

Shale gas is a type of "unconventional" natural gas embedded in shale rock formations (The Royal Society, 2012). These sedimentary formations are composed from mud, silt, clay and organic matter. It is this organic matter that natural gas (shale gas) was over the eons formed from (British Geological Survey, 2013), now being found at depths of 1 to 4 km (The Royal Society, 2012). This type of gas has almost identical composition as conventional gas, mostly composes of methane, but other gases may be present as well, only difference is that shale gas is usually quite dry (Stephenson et al., 2011; The Royal Society, 2012). Main difference between shale gas and conventional sources of gas is that shale gas does not flow from the well by itself (British Geological Survey, 2013). In the case of conventional wells, gas starts to spontaneously flow from the well the moment the well is completed. To make the distinction simpler, when a conventional well is drilled, gas flows spontaneously in commercial quantities, in the case of unconventional wells such as shale gas, the gas does not flow in commercial quantities and special extraction techniques are required (Stevens, P., 2012). This is caused by much lower permeability of the shale formations compared to the permeability of the rock formations where the conventional gas occurs (rock formations with permeability of around 1000 microdarcy) (Stephenson et al., 2011). In the case of shale gas, the gas is trapped in shale rock formation with permeability less than 1 microdarcy (Stephenson et al., 2011) and special technique called hydraulic fracturing (often "fracking") needs to be used to virtually crack the shale rock and release the trapped gas (British Geological Survey, 2013).

Fracking is an extraction method specific in the case of shale gas (possibly in the future shale oil as well) when large quantities of liquid are pumped into the well under high pressure (The Royal Society, 2012). This pressure overcomes the power of the shale rock which cracks and releases the gas embedded in it, which consequently flows through the well to the surface where it is collected and further processed (Stephenson et al., 2011). Liquid used in this process composes mainly from water, but also other additives such as sand and various chemicals are present (The Royal Society, 2012). Send is used to keep the cracks in the rock open for the gas to flow after the pressure of the liquid decreases and water retreats. Other chemicals and acids are added mostly to improve the viscosity of the fluid in order to enable smoother fracking process and help to dissolve the rock (Stephenson et al., 2011).

Even though fracking emerged in commercial scale only recently, its history can be traced back to the year 1947 when the first US shale gas well was fracked (Stevens, P., 2012). The origins of horizontal drilling can be traced even further back to 1930's (Stevens, P., 2012). Focusing only on the UK, first well ever drilled into a shale rock formation is dated into the year 1875 probing for gas in the Upper Jurassic Kimmeridge clay (Selley, R., C., 2011). Nevertheless, this operation did not involve either horizontal drilling or hydraulic fracturing and its significance was not realized at the time (Selley, R., C., 2011). First evaluation of the UK's shale gas reserves did not occur until 25 years ago when researchers from the Imperial College of London applied the US shale gas paradigm in the UK's condition for the first time ever (Selley, R., C., 2011). Still, it took two and a half decade since then for the first commercial shale gas well to be drilled in the UK (Selley, R., C., 2011)

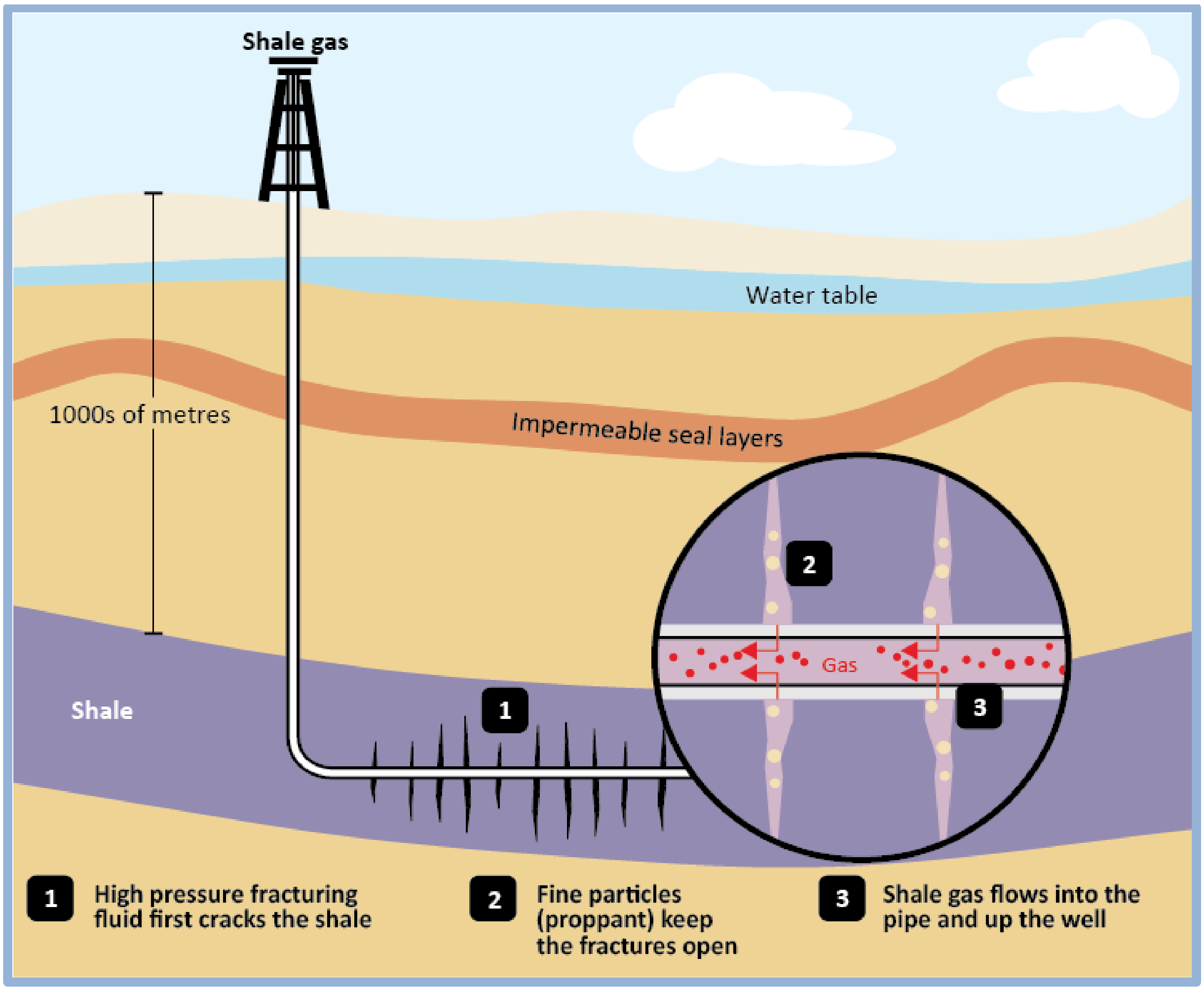

Figure 1: **Shale gas extraction method**, *Source: Department of Mines and Energy (2013)*

Opposers of shale gas extraction mostly argue with the higher emission levels comparing to the conventional natural gas production caused by the above described fracking. In the past several years, various studies closely examined this question (Jiang et all., 2011; Stephenson et al., 2011). Even though results still suggest higher end-of-the-pipeline emissions of shale gas production comparing to conventional production, difference is not as dramatic as previously thought. Life cycle greenhouse gas emissions analyses conducted by (Jiang et all., 2011) on the example of Marcellus shale formation suggest that shale gas extraction emissions exceed those of conventional production only by 11% when the combustion is not taken into consideration and by only 3% when combustion emissions are included. Stephenson's et al., (2011) research modeling relative GHG emissions from shale gas and conventional onshore gas production suggests that the difference in emissions equals to 1.8 – 2.4% and only under the extreme conditions can reach as high as 15%. Model developed by Burnham et al., (2011) presents surprising results stating that shale gas emissions are actually 6% lower than those of conventional production, but in this case, even the author admits high levels of statistical uncertainties due to the overlapping data. Study conducted by the Cranfield University (2013) suggests that the difference hovers around 20 % (before the combustion phase) depending on whether the conventional onshore or conventional offshore natural gas sources are considered.

As there is a general consensus amongst researchers that shale gas emissions are higher than those of conventional production, it is also widely agreed that they are still significantly lower than those of other fossil fuels such as coal or oil, especially when it comes to electricity generation. Jiang et all., (2011) states that when natural gas obtained from Marcellus shale formation is used for electricity generation, carbon emissions created this way are 20 – 50 % lower than in the case of coal-fired electricity generation. Another study comparing shale gas emissions with the emissions of other types of fossil fuels conducted by Burnham et al., (2011) states that life cycle GHG emissions of shale gas are 24% lower than oil and 33% lower than coal emissions, after the combustion phase during electricity generation.

Another important fact leading to the frequent revisiting of the shale gas question is that the estimated technically recoverable shale gas reserves are thought to be almost three times higher than proven conventional natural gas reserves worldwide (456,241km^3 (16,112 tcf) of estimated technically recoverable shale gas reserves comparing to 187,146 km^3 (6,609 tcf) of conventional proven reserves (Stevens, P., 2012). Another prediction made by Rahm, et al., (2012) states that after the estimated shale gas reserves will be proven, overall technically recoverable world natural gas resources are expected to grow by at least 40%.

Shale gas in the UK

Several studies have been conducted mapping unconventional hydrocarbon resources such as shale gas in the UK (Richards, P. and Fell, M., 2013). Majority of the shale gas is thought to be located in the Upper Bowland Shale, Kimmeridge Clay and Lias of the Weald Basin rock formations (Richards, P. and Fell, M., 2013). A report from the UK Energy Research

Centre (UKERC, 2012) points out the much lower recovery rates of the shale gas which are somewhere between 15 – 30% of the shale gas reservoir capacity. Conventional wells are thought to have recovery rates of about 80% (Richards, P. and Fell, M., 2013). 2013 report provided by BGS/DECC (2013), based on the gas yields of US shale gas industry sets UK's shale gas recoverable resources somewhere between 51 to 368 km^3 (1.8 to 13 tcf) using a similar recovery rates of 8 – 20%. Yet another study conducted by US Energy Information Administration (2013) estimates the UK's shale gas recoverable resources to be as high as 736 km^3. Cuadrilla, company already drilling in the Bowdal shale published its estimates of 161 km^3 (5.7 tcf) of technically recoverable shale gas in the Bowdal shale itself (Cuadrilla, 2010).

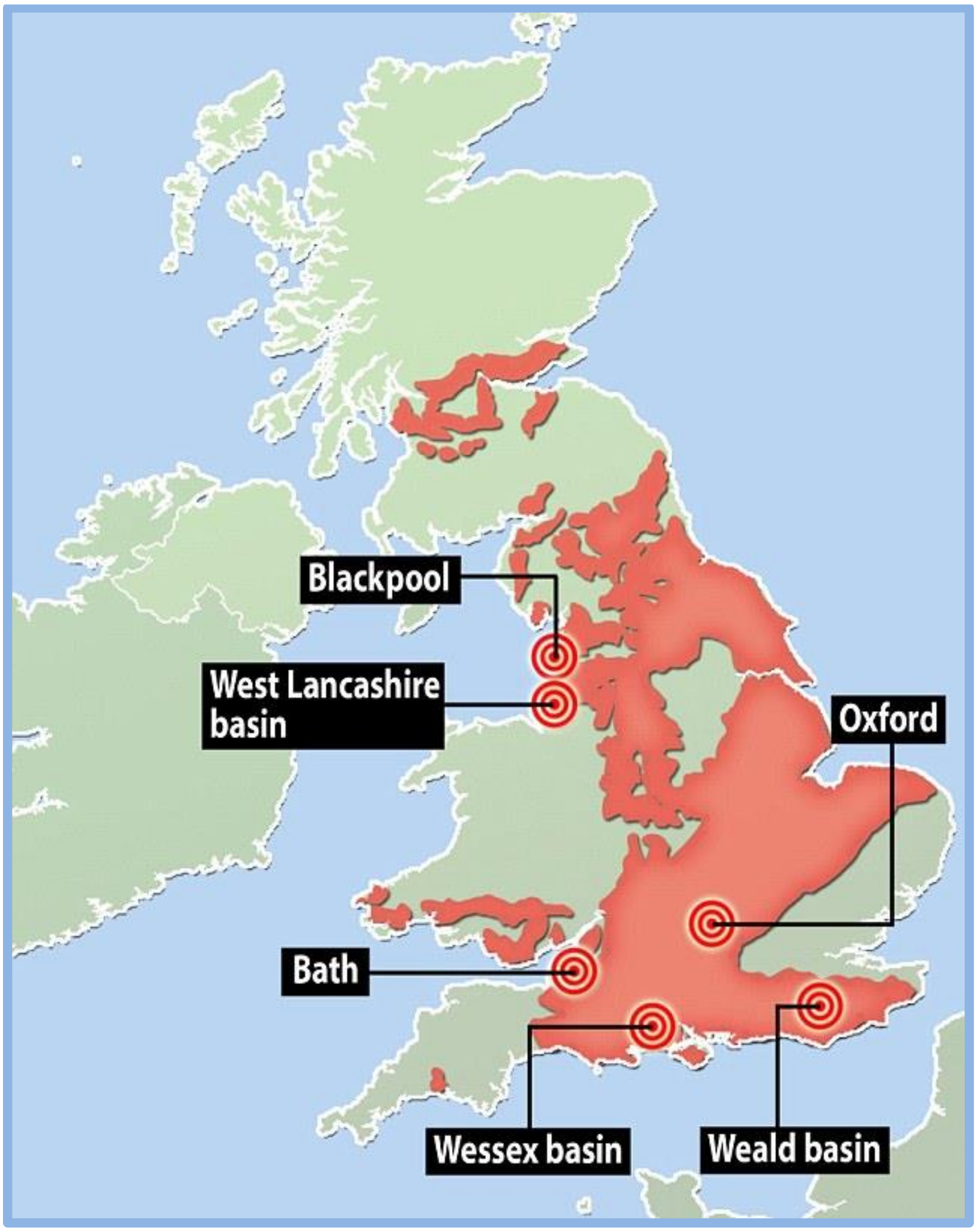

Figure 2: **Locations where is shale gas thought to be present**, *Source: dailymail.co.uk (2013)*

Natural gas demand and supply in the UK

Even though the overall natural gas demand in the UK seemed relatively stable in the past 2 decades (its variations are less than 10% of its nominal values (GOV.UK, 2013b)), its inner blend is anything but that. Turbulences inside the UK's natural gas demand blend are mostly caused by changes in the UK's electricity generation sector which is transforming from coal and oil based towards modern, low-carbon system using natural gas as a transition tool.

For more than a century, coal has been the main fuel source for electricity generation not only in the UK but literally all over the world. Coal fired industrial revolution, which carved the world into the shape as we know it now. Coal fired heavy industry through, in-between, and after the both world wars but recent environmental restrictions and governmental regulations with all the probability signal the last chapter of the coal fired power generation. Directives originating from the European Union such as Large Combustion Plant Directive (LCPD) or Industrial Emissions Directive (IED) (Defra, 2010) effectively mean that the era of mammoth coal-fired power plants is coming to its early end. Experts agree that the last large coal fired power plants will close no later than in the mid-20's (Odeh, et al., 2007; Defra, 2010). The rate in which the coal fired power plants are going to close depends mostly on the decisions of individual plants how to used "running hours" allocated to them by the government (Defra, 2010). Only way which could possibly ensure survival of at least some coal-fired power plants is use of Carbon Capture and Storage (CCS) technology. CCS is an expensive technology allowing use of cheap fuel (coal) to be still used even under directives LCPD and IED (Odeh, et al., 2007). Nevertheless decline in the natural gas prices due to the US shale gas revolution may mean that use of cheap natural gas is going to prove to be more profitable than employing such an expansive technology as is CCS (Odeh, et al., 2007).

Another mean of electricity generation is Oil. Oil-fired electricity generation has never reached the magnitude of the coal-fired one but still it is considered to be one of the traditional electricity sources for the UK. Especially in the period from 70's till mid-80's UK's oil fired electricity production used to cover roughly 20 percent of the UK's electricity demand (GOV.UK, 2013a). Nevertheless, since those days, its share in the electricity generation sector is gradually decreasing and oil fired power generation is presumed to cease completely in the next decade or so (GOV.UK, 2013a, Defra, 2010).

Also traditional, but with prospects towards much brighter future are nuclear power plants. Nuclear electricity generation in the UK started as soon as in the mid 1950' but it took a decade and a half or so for it to become a significant source of electricity for the UK (GOV.UK, 2013a). Since the early 70's, nuclear power plants steadily generate 15 – 25 percent of the UK's electricity. Despite this well established tradition of nuclear electricity generation, 8 out of nine currently running nuclear power plants are scheduled to be decommissioned by the year 2023 (table 1) and no new are being built (World Nuclear Association, 2013), partially due to the influence of the Fukushima disaster (Apte et al., 2011; Stevens, P., 2012) This fact alone does not have to necessarily mean that nuclear electricity generation will meet the same end as the coal or oil fired ones. Recently, several new proposals regarding building of new nuclear power plants arose (table 1) and even public perception seems to shift back towards the nuclear electricity generation as research conducted by Bickerstaff et al., (2008) shows. Furthermore, cost benefit analysis of nuclear power generation against other major electricity sources conducted by Kennedy, D., (2007) shows that nuclear power plants seem to be economically beneficial in almost all the scenarios modeled in his study.

Given by the UK’s location and weather conditions, wind power is its most promising renewable source of electricity. In its short history which begins somewhere in the mid-1990’s, proportion of electricity supplied by the wind farms has grown substantially. Until today, there are installed over 5.3 GW of wind farms. These can be divided into onshore and offshore wind farms producing 7 and 3 TWh of electricity respectively (Department of energy & climate change, 2011). Department of energy & climate change (2011) made as well a prediction that by the year 2020 installed onshore wind capacity will reach 13 GW and offshore wind deployment could reach 18 GW by the same year, with a great potential to reach up to 40 GW by the ear 2030. Research presented by Sinded, G., (2005) suggests weak but obvious correlation between wind patterns and electricity demand fluctuations, making the wind-generated electricity production less susceptible to the peak electricity demand. Major obstacles the wind electricity generation faces in the UK are construction costs and subsequent increase in electricity prices in the case of offshore wind (Dale et al., 2004; Toke, D., 2010) and various landscape protection interests causing 60% of the wind farms proposals to be dismissed in the case of onshore wind (Dale et al., 2004).

During its almost a century long history, hydroelectric power made nothing but a modest contribution into the UK’s electricity mix with level of deployment hovering between one and two percent of the total UK’s generating capacity. This technology does not even hold a significant potential to the future because most of economically interesting locations for this technology have already been developed (GOV.UK, 2011). Recent studies suggest that there is a potential for development worth of 0.85 to 1.55 TW of generating capacity still existing in the UK (GOV.UK, 2011).

In addition to the previously mentioned, there are many other electricity sources. These are mostly already obsolete and at the end of the time period when they can be actually economically profitable on one hand, and electricity sources which are brand new, in their early stage of development or deployment on the other hand or electricity sources which are common elsewhere but for any reason are not used in the UK in a commercial scale (solar farms, bio gas plants, tidal and sea current power plants, bio mass, etc.).

Since the electricity sources predominant in the past (coal, oil) are being decommissioned much faster than new, low-carbon sources can kick in (wind), natural gas demand in the electricity generation sector is growing rapidly and in the decades to come, natural gas is expected to be predominant fuel input for electricity generation (Grubb et al., 2005; Stern, J., 2004). Even though natural gas demand besides the electricity generation (heating, transport, etc…) is slowly decreasing (GOV.UK, 2013a), it is not decreasing fast enough and due to the significant growth in the share of gas-fired electricity generation In the UK's electricity generation sector, UK's overall natural gas demand is expected to rise. (Stevens, P., 2012). Such an increase in the demand would not present a serious problem for the UK a decade or two ago, but many has changed since those days.

Until the year 2005, UK conventional production was able to cover virtually all the UK's natural gas demand (GOV.UK 2013b), but its sharp decrease since then means that the UK had to start to search for alternative sources of natural gas such as pipeline imports, LNG, or recently, shale gas. In past 10 years UK conventional production dropped from some 1200 TWh onto as low as 520 TWh a year and is predicted to continue to decline (GOV.UK 2013b). However, the rate in which the UK's conventional production is going to decline is yet to be seen. Research conducted by Kong Chyong Chi et al., (2008) suggests that the major reason for the UK's today's rapid decline of conventional production are decisions of previous governments to support as fast exploration of the UK's conventional reserves in order to support large scale exports. UKCS (2013) made a prediction about the UK's future conventional production but this prediction seems rather optimistic, saying that the sharp decrease of the production will suddenly stop in the year 2013 and the production rate will stabilize till the year 2018 when it will start to slowly decrease again. Previous research suggests (Cranfield University, 2013) that indigenous conventional production is the most environmentally friendly way of natural gas sourcing with end-of-pipeline emissions of "only" 0,041 kg of CO_2e / kWh released into the atmosphere per kWh of natural gas produced for onshore production and 0,044 kg of CO_2e / kWh for offshore production.

The second least polluting way of sourcing of natural gas is through pipeline imports (Cranfield University, 2013). Currently, there are 5 pipelines supplying the UK with natural gas (table 3). Three originate in Norway, one in Belgium and one in the Netherlands. Their combined maximum capacity is close to 1 000 TWh a year (947.36) but currently they are being used only from 40% or so (table 4). Recently, topic of building yet another pipeline to the UK has been revisited by experts and British government (NEWEUROPE, 2012). Additional emissions caused by pipeline transport of natural gas equal “only” to 5 gCO_2/ton-km.

The most polluting way of sourcing of natural gas the UK is currently using is LNG imports. Since the year 2005 when the UK imported first significant amount of the LNG, its imports grew significantly from around 5.5 TWh in the year 2005 to more than 270 TWh in the year 2011 (GOV.UK, 2013d). Emission factor developed by the Cranfield University equals to 0.02 CO_2e / kWh which account only for the liquefaction and regasification process. LNG transport emissions are similar to pipeline transport emissions and equal to 5.319 gCO_2/ton-km.

When it comes to the question of sourcing of natural gas, the most important factor influencing decision making process is the costs. The obvious one is of course the cost of the gas itself but natural gas use has also hidden costs such as carbon costs.

European natural gas market exists along the lines of the market with crude oil and is predominantly binded by the long-term contracts (Weijermas et al., 2010; Apte et al., 2011) This effectively means that natural gas price does not develop independently but is highly influenced by the price of crude oil, even though there might be factors having an effect on the gas price outside the crude oil market, as for example prices of another commodities of similar sort such as coal. The reason for several separate natural gas markets around the globe is so called “tyranny of distance”” as natural gas is high-volume and low-price commodity (Stevens, P., 2010). Only recently new phenomenon emerged caused by the American shale gas revolution. Large-scale shale gas extraction in the US caused oversupply of LNG on the gas market (American and subsequently European) which lead to at least partial decoupling of natural gas and crude oil prices even on the European market (Stevens, P., 2012; Weber et al., 2012; Ridley, M., 2011). Some studies such as for example Apte et al., (2011) even see the future decoupling of European crude oil and natural gas prices as unavoidable. Wholesale natural gas price has been fluctuating in the past, as previously mentioned influenced by the crude oil price, but its gradual increase can be easily noticed (GOV.UK, 2013e). As for the future natural gas prices, GOV.UK (2013e) made a prediction that wholesale natural gas prices should more or less stabilize on the level of around 2.5 p/kWh as a consequence of the combination of downward pressure put on the gas price by oversupply of LNG and its natural tendency to grow (Stevens, P., 2012)

Besides its direct price, use of natural gas has additional costs in a form of carbon costs expressible in the prices of emission allowance. European emission trading scheme (EU

ETS) is a tool used by the EU to limit greenhouse gas emissions. EU ETS uses so called EUA (EU emissions allowance) to achieve that. EUA is basically a permitted amount of GHG emissions which is each country allowed to release into the atmosphere (European Commission, 2013). These permits are tradable and are a convenient tool how to express cost of GHG emissions in monetary terms. The EUA prices fluctuate greatly depending on the phase of the EU ETS and willingness of factories to limit their emissions (European Commission, 2013). Research conducted by (Alberoal et al., 2007) suggests that immense fluctuations in the EUA prices were caused by their oversupply on the market rather than just by energy prices and unexpected weather condition as previously thought.

METHODOLOGY

Frame of reference

This study examines the UK's natural gas demand using analysis of the UK's electricity generation system and demand for natural gas in it, which together with broader natural gas demand forms the UK's overall natural gas demand. High levels of predicted future installed capacities (especially in the case of nuclear and wind power generation (World Nuclear Association, 2013; Department of energy and climate change, 2011)) have been used, even though there is a chance that these capacities will not be fully reached in the referred time frame. Furthermore, many studies tend to separate electricity storage and imports into distinct categories (Department of energy and climate change, 2012), this study operates with the assumption that the UK is going to be energetically self-sufficient in the future so these categories bare little or no significance (>1%) and are included in the section "other". Even though the UK still exports some of its natural gas, these exports are not included in this study because UK's own natural gas mix is the subject of research. Natural gas exports were removed (not neglected) from the data used as bases for this study.

When the natural gas demand is estimated, this research proposes the optimal composition of the UK's natural gas mix based on the UK's own conventional resources, pipeline imports, LNG imports and the shale gas potential lurking beneath the UK. Due to the huge variance in available estimates, this study uses mid-range of 566 km^3 (20 TCF) of technically recoverable shale gas in the UK, supported by The Royal Society (2012) and British Geological Survey (2013). During the creation of the model for estimation of the future values and compositions, carbon footprint has always been put ahead of the price, therefore the results tend to present the least environmentally harmful outcomes rather than the most probable ones or the outcome most desirable by the government.

At the end of this chapter, methods used for calculation of the commodities prices such as the natural gas itself or EUA are presented. Due to the fact that frame of reference of this study is 35 years (time period 1995 – 2030) and many data is available only in euros, long term value of £0.85 = €1 is used throughout the entire length of this study. It goes well beyond the point of reference of this study to try to incorporate changing currency rates or try to estimate the future ones.

UK electricity generation fuel inputs mix

For the purpose of this study the UK natural gas demand has been divided into two mutually not over-lapping sections, Natural gas required for the electricity generation and the rest used for other purposes (heating, transport, etc.) Several sub-chapters below describe methodology used to estimate the UK's future electricity generation fuel input mix and subsequently the amount of natural gas needed for electricity generation in the future.

Means of electricity generation in the UK

This chapter examines the role of natural gas in the UK's natural gas mix using analysis of the fuel input into electricity generation data provided by GOV.UK (2013a). This data provide fuel inputs into electricity generation of the six main UK's means of electricity generation: coal, oil, nuclear, wind, hydro and other (solar farms, bio gas plants, tidal and sea current power plants, bio mass, etc.). Future estimates are based on the predictions made by particular authorities and experts, complemented by a statistical estimation in cases when the data or predictions are missing or the bases of these predictions are not consistent with assumptions this study is based on.

Coal

Experts agree that last large coal fired power plants will close no later than in the mid 20's under the directives LCPD and IED (defra, 2010). This means that coal fired power generation will cease to have a significant impact (>1% of the UK's overall electricity production) on the UK's fuel input for power generation mix by the end of the year 2024.

Calculation method:

Future prediction was constructed on the bases of continual decrease of the coal fired electricity generation until the year 2025, when it is presumed to descend below the level of significance this study takes into consideration.

In the year 2012 coal-fired power plants produced 325 TWh of electricity (GOV.UK, 2013a) and are presumed to completely cease their production by the year 2025 (defra, 2010).

Equation:

$$y_{c_n} = z - \frac{z}{x_{13} - x_1} * x_n$$

y_c = value for the year x_n (TWh)
x_n = time vector (year 2013 = x_1 = 1, year 2014 = x_2 = 2 …)
z = electricity produced in the year 2012

The rate of decline of the coal fired electricity generation depends mostly on the decisions of individual plants how to used “running hours” allocated to them by the government (GCRP, 2007) which makes the real shape of the curve A – C infeasible to predict. Size of the area A – B – C should stay virtually unchanged regardless the shape of the curve A – C though, because this area roughly represents operating time allocated to the coal fired power plants by government through previously mentioned “running hours” (figure 3).

Oil

Based on the data provided by GOV.UK (2013a) (data from 1995 to 2011 were used) linear regression has been performed suggesting that contribution of the oil fired power gelation will drop beneath the levels this study recognizes as significant by the year 2017. Linear regression has been chose due to the almost neglectable share of the oil based electricity generation in the UK.

Calculation method:

Equation:

$$y_{o_n} = -1.4372 * x_n + 32.647$$

y_o = value for the year x_n (TWh)
x_n= time vector (year 1995 = 1 = x_1, year 1996 = 2 = x_2 …)

Nuclear

Model developed to estimate the future nuclear based electricity generation in the UK takes into account changes in the UK’s nuclear based generating capacity showed by the table 1. Generation capacity available in each year has been adjusted according to data provided by World Nuclear Association (2013) indicating years when old plant are going to be decommissioned and new plants built. Amount of generated electricity directly correlates with the available generating capacity.

Table 1: **list of existing, planed and proposed nuclear power plants in the UK,** *source:* World Nuclear Association (2013)

Existing				
Plant	Type	Present capacity (MWe net)	First power	Expected shutdown
Wylfa 1	Magnox	490	1971	Sep 2014
Dungeness B 1&2	AGR	2 x 545	1983 & 1985	2018
Hartlepool 1&2	AGR	2 x 595	1983 & 1984	2019
Heysham I-1 & I-2	AGR	2 x 580	1983 & 1984	2019
Heysham II-1 & II-2	AGR	2 x 615	1988	2023
Hinkley Point B 1&2	AGR	2 x 610, but operating at 70% (430 MWe)	1976	2023
Hunterston B 1&2	AGR	2 x 610, but operating at 70% (420 MWe)	1976 & 1977	2023
Torness 1&2	AGR	2 x 625	1988 & 1989	2023
Sizewell B	PWR	1188	1995	2035
Total: 16 units		10,038 MWe		
Proposed and planed				
Hinkley Point C-1	EPR	1670	2018	NA
Hinkley Point C-2	EPR	1670	2019	NA
Sizewell C-1	EPR	1670	2020	NA
Sizewell C-2	EPR	1670	2022	NA
Oldbury B	ABWR x 2 or 3	2760-4140	by 2025	NA
Wylfa B	ABWR x 2 or 3	2760-4140	by 2025	NA
Moorside	AP1000? x3	Up to 3600	2023	NA
Total planned & proposed		Up to approx. 18,600 MWe		

Calculation method:

Installed capacity of 10 038 MWe in the year 2011 produced 182 TWh electricity. This study takes this as a baseline and future prediction is calculated as electricity production from the year 2011 multiplied by percent change in generating capacity in each year, compared to the year 2011.

Equation:

$$y_{n_n} = z * \frac{x_n}{w}$$

y_n = value for the year x_n (TWh)

x_n= momentary capacity (year 2011 = x_1 Year 2012 = x_2 …)

z = electricity generated in the year 2011

w = generating capacity in the year 2011

Table 2 **Bases for the nuclear electricity generation calculations**

Year	Electricity produced (TWh)	Installed capacity (MWe) (x_n)	Capacity decommissioned (MWe)	Capacity commissioned (MWe)	% of 2011 capacity in operation
2011	181,7304	10 038			100
2012	181,7304	10 038			100
2013	181,7304	10 038			100
2014	172,8593	9 548	490		95
2015	172,8593	9 548			95
2016	172,8593	9 548			95
2017	172,8593	9 548			95
2018	183,3598	10 128	1 090	1 670	101
2019	171,0489	9 448	2 350	1 670	94
2020	201,283	11 118		1 670	111
2021	201,283	11 118			111
2022	231,517	12 788		1 670	127
2023	207,6194	11 468	4 920	3 600	114
2024	207,6194	11468			114
2025	357,5226	19 748		8 280	197
2026	357,5226	19 748			197
2027	357,5226	19 748			197
2028	357,5226	19 748			197
2029	357,5226	19 748			197
2030	357,5226	19 748			197

Wind

Today, there are installed over 5.3 GW of wind farms. These can be divided into onshore and offshore wind farms producing annually 7 and 3 TWh of electricity respectively (Department of energy & climate change, 2011).

To estimate amount of electricity supplied to the UK's grid by the onshore wind farms in the future, this study takes into consideration prediction made by Department of energy & climate change (2011) which states that by the year 2020 installed onshore wind capacity will reach 13 GW, Time period 2020 - 2030 has been estimated using linear regression in order to maintain the integrity of this study. Same approach has been chosen in the case of offshore wind. Department of energy & climate change (2011) made a projection which says that offshore wind deployment could reach 18 GW by the end of this decade, with a great potential to reach up to 40 GW by the year 2030. Same as in the case of nuclear power generation, generating capacity in GW correlates with TWh of electricity produced.

Calculation method:

Future prediction was constructed on the bases of continual increase of the onshore wind farm deployment until the year 2020, when it is forecasted to reach generating capacity of 13 GW (Department of energy and climate change, 2011), for the integrity of this study, values for the time period 2020 – 2030 were calculated using linear regression. Future prediction for the offshore wind was constructed on the bases of continual increase of the electricity generation capacity until the year 2020, when it is forecasted to reach generating capacity of 18 GW,. The same forecast continues saying that offshore wind deployment is expected to reach 40 GW by the year 2030 (Department of energy and climate change, 2011)

In the year 2010 onshore wind generating power deployment reached 4 GW of operational capacity, producing 7 TWh of electricity. Prediction says that expected onshore wind generating capacity in the year 2020 will be 13 GW.

In the year 2010 offshore wind deployment reached 1.3 GW of operational capacity, producing 3 TWh of electricity Prediction says that expected offshore wind deployment in the year 2020 is expected to be 18 GW and in the year 2030 it is expected to be as high as 40 GW.

Parameters for the time period 2011 – 2020:

$y_{w(a\ or\ b)}$ = *value for the year* x_n *(TWh)*
x_n= *time vector (year 2011 = 1 =* x_1 *Year 2012 = 2 =* x_2 *…)*
z = electricity generated in the year 2010
w_a = *generating capacity in the year 2010*
w_b = *generating capacity in the year 2020*

Parameters for the time period 2020 – 2030 (offshore only):

Y_{wb} = *value for the year* x_n *(TWh)*
x_n= *time vector (year 2020 = 1 =* x_1 *Year 2021 = 2 =* x_2 *…)*
z = electricity generated in the year 2020
w_a = *generating capacity in the year 2020*
w_b = *generating capacity in the year 2030*

Equation:

$$y_{wb_n} = z + \frac{w_{b-}w_a}{x_{10} - x_1} * \frac{z}{w_a} * x_n$$

Due to the missing forecast for the onshore wind, time period 2021 to 2030 has been calculated using linear regression

Equation:

$$y_{wa_n} = -0.9807 * x_n - 5.4417$$

Y_{wa} = value for the year x_n (TWh)
x_n= time vector (year 1995 = 1 = x_1, year 1996 = 2 = x_2 …)

For the further calculations, this study uses combined values of the onshore and offshore wind under the designation „wind".

$$y_w = y_{wb} + y_{wa}$$

Hydroelectric

For the future prediction of electricity generated this way, this study uses linear regression approach. This is because the contributions of hydroelectric power to the grid were relatively slowly but steadily growing in the past, and previously mentioned undeveloped potential suggests that this modest growth will continue even in the foreseeable future. As bases for this prediction data provided by (GOV.UK, 2013a) (data from the year 1995 to 2011) have been used.

Calculation method:

Equation:

$$y_{h_n} = 0.0354 * x_n + 4.34$$

y_h = value for the year x_n (TWh)
x_n= time vector (year 1995 = 1 = x_1, year 1996 = 2 = x_2 …)

Other

This category composes from all electricity sources with low contribution to the electricity grid, which for the purpose of this study, do not require further distinction. These are mostly already obsolete and at the end of the time period when they can be actually economically profitable on one hand, and brand new, in their early stage of development or deployment on the other hand. This category also includes electricity sources which are common elsewhere but for any reason are not used in the UK (solar farms, bio gas plants, tidal and sea current power plants, bio mass, etc.).

Due to almost linear growth of this category in the past, this study uses linear regression to estimate its future contribution to the UK's. Future prediction is developed based on the data provided by GOV.UK (2013a) (data from the year 1995 to 2011 have been used).

Calculation method:

Equation:

$$y_{t_n} = 2.7977 * x_n + 18.547$$

y_t = value for the year x_n (TWh)

x_n= time vector (year 1995 = 1 = x_1, year 1996 = 2 = x_2 …)

Fuel inputs into electricity generation demand

In order to determine how much natural gas is the UK going to need in the future, overall fuel input into electricity generation demand has been estimated. Due to the fact that its fluctuations in the past 15 years were not larger than 10 % of its nominal values, also in this case, linear regression has been used based on the data provided by (GOV.UK, 2013a) (data from the year 1995 to 2011 have been used).

Calculation method:

Equation:

$$y_{d_n} = 1.3382 * x_n + 936.65$$

y_d = value for the year x_n (TWh)

x_n= time vector (year 1995 = 1 = x_1, year 1996 = 2 = x_2 …)

Role of natural gas in the UK electricity generation

The gap between the estimated fuel inputs for electricity generation demand curve and the levels of inputs provided by the means described above is a gap which is going to have to be filled with natural gas.

Calculation method:

Values of all the previously mentioned UK's means of electricity generation have been put together and compared with the overall demand calculated in the previous chapter.

Equation:

$$y_{ga} = y_d - (y_c + y_o + y_n + y_w + y_h + y_t)$$

Overall natural gas demand

The amount of natural gas calculated above, used for electricity generation, by far does not cover whole UK's natural gas consumption. Large quantities of natural gas are also being used for other purposes such as heating, transport, industries, etc. This amount has been steadily decreasing in last 15 years and is expected to continue doing so in the. Use of the natural gas besides the electricity production has been calculated based on data provided by GOV.UK (2013b) (data from the year 1998 to 2011 have been used) using linear regression. This approach has been chosen due to its stable trend in the past, and no known circumstances altering this trend in the future.

Calculation method:

Due to the effort to maintain the consistency of this study, missing data for the years 1995 – 1997 have been calculated.

Equation:

$$y_{gb_n} = -11.603 * x_n + 829.36$$

y_{gb} = value for the year x_n (TWh)

x_n= time vector (year 1995 = -3 = x_{-3}, year 1996 =-2 = x_{-2} …)

When the data series has been completed, linear regression has been used to estimate the future values.

Equation:

$$y_{gb_n} = -12.2 * x_n + 871.59$$

y_{gb} = value for the year x_n (TWh)

x_n= time vector (year 1995 = 1 = x_1, year 1996 = 2 = x_2 …)

Overall natural gas demand has been calculated by combining amounts of natural gas necessary for electricity generation and non-electricity generation use.

Equation:

$$y_g = y_{ga} + y_{gb}$$

UK natural gas mix

After the amount of natural gas the UK is going to need in the future has been estimated, closer look into its composition has been taken. This chapter describes the main ways (UK conventional production, Pipeline imports, Shale gas and LNG) how the UK could source its natural gas in the future.

UK conventional production

In order to provide as objective estimates as possible, this study uses prediction made by UKCS (2013) completed by linear regression to estimate the future UK's conventional natural gas production. Further, due to the missing data, the production from the years 1995 to 1997 has been calculated back based on the data provided by (UKCS, 2013) in order to complete the data series and maintain the consistency of this study. Data from the years 1995 to 1997 do not have to necessarily exactly reflect the real situation from those years and are purely of an auxiliary character.

Calculation method:

First, prediction made by UKCS (2013) has been taken into account.

Prediction for the year 2012 (TWh) = 407 (y_{pa1})
Prediction for the year 2013 (TWh) = 407 (y_{pa2})
...
Prediction for the year 2029 (TWh) = 221 (y_{pa18})
Prediction for the year 2030 (TWh) = 209 (y_{pa19})

Second, missing data for the years 1995 – 1997 have been calculated back.

Equation:

$$y_{pb_n} = -50.392 * x_n + 1356.5$$

y_{pb} = value for the year x_n (TWh)

x_n= time vector (year 1995 = -3 = x_{-3}, year 1996 = -2 = x_{-2} …)

Third, due to the fact that this study considers UKCS (2013) prediction rather optimistic than realistic, statistic approach to estimate the future production has been applied.

Equation:

$$y_{pb_n} = -37.421 * x_n + 1346.5$$

y_{pb} = value for the year x_n (TWh)

x_n= time vector (year 1995 = 1 = x_1, year 1996 = 2 = x_2 …)

Finally, because the UKCS (2013) prediction has been found to optimistic on one hand and results of the statistical approach were suggesting unrealistically steep decline of the UK's conventional production, this study uses averaged values of the two previously mentioned.

Equation:

$$y_p = \frac{y_{pa} + y_{pb}}{2}$$

Pipeline imports

To estimate the future pipeline exports to the UK has proven to be highly demanding. The approach finally chosen was to calculate average percentage utilization of all the pipelines since the year 2000 (pipelines BBL, Lnageled and FLAGS have been put into operation after the year 2000) based on the data provided by GOV.UK (2013d) and Statoil (2013). When the average utilization in each year has been calculated, its values have been extrapolated using the trend line up to the year 2030, which is the end of the period this study examines. As far as this study goes, it is not important to try and distinguish between the pipelines and their individual contributions, and all the future pipeline imports are calculated with as one.

Table 3: Natural gas pipelines to the UK, *Source: transported amounts: GOV.UK (2013d), pipeline capacities: Statoil (2013).*

Name	Country	Commissioned	Capacity (billion m^3-year)	Transported since year 2000 (TWh)	Use (%)
Vesterled	Norway	1978	13.14	796	44
FLAGS	Norway	2003	9.67	196	19
Langeled	Norway	2006	24.82	1098	59
BBL	The Netherlands	2006	16	480	40
Inteconnector	Belgium	1998	25.5	157	4

Calculation method:

Growth in the percentage utilization of the pipeline capacity has been extrapolated into the future using data since the today's pipeline capacity of 947 TWh has been commissioned in the year 2006 (table 3).

Equation:

$$y_i = 0.0211 * x_n + 0.2628$$

y_i = value for the year x_n (%)

x_n= time vector (year 2006 = 1 = x_1, year 2007 = 2 = x_2 …)

Table 4: Bases for pipeline utilization calculations

Country	Belgium	Netherlands	Norway			Total	pipeline capacity use	Capacity
Name	Interconnector	BBL	Langeled	FLAGS	Vesterled			
Year	TWh	TWh	TWh	TWh	TWh	TWh	%	TWh/year
2000	2,96				11,28	14,23	3,47%	411
2001	4,02				12,73	16,75	4,08%	411
2002	6,65				37,89	44,53	10,84%	411
2003	4,39			0,69	71,07	76,14	14,83%	513
2004	25,59			10,60	84,76	120,95	23,55%	513
2005	24,11			8,10	119,80	152,00	29,60%	513
2006	30,51	9,14	43,95	3,31	109,77	196,67	20,76%	947
2007	6,47	76,60	140,34	10,33	75,10	308,84	32,60%	947
2008	12,17	90,56	175,54	26,01	82,17	386,46	40,79%	947
2009	7,95	69,53	179,95	22,47	58,02	337,91	35,67%	947
2010	13,57	87,12	194,28	23,42	59,11	377,49	39,85%	947
2011	4,03	69,00	165,57	37,28	31,35	307,23	32,43%	947
2012	14,26	78,26	197,98	53,50	43,10	387,11	40,86%	947

Shale gas

As more closely described in the background section, there are about 566 cubic kilometers (20 trillion cubic feet) of technically recoverable shale gas estimated to be beneath the UK (The Royal Society, 2012). Using average lifetime output of a shale gas well of approximately 85 million m^3 and its life-span of 30 years (NETL, 2011), this translates roughly into 6500 shale gas wells needed for the extraction of all the gas. When recalculated into energy units, this translates approximately into 0.03 GWh/well-year and altogether into 200 TWh worth of shale gas possibly being produced in the UK annually.

LNG

Liquefied natural gas is the last of the four major sources of natural gas the UK is currently using. It is also the youngest and the most rapidly growing one, despite the fact that it is also the most polluting source of natural gas.

Since the year 2005 when the UK imported first significant amount of the LNG, its imports grew significantly from around 5.5 TWh in the year 2005 to more than 270 TWh in the year 2011 (GOV.UK, 2013d). Nevertheless its annual amounts are expected to decrease in the years to come.

Natural gas blend

After the estimation of the values of natural gas sources the UK can use in the future, resultant bled has been composed. This blend composes of the UK's conventional production and expected pipeline imports compared to the UK's overall natural gas demand. Role of LNG and shale gas in it is to be determined in the discussion section.

Calculation method:

Whether there is a room for shale gas (or LNG) in the UK's natural gas blend is to be determined by comparing the UK conventional production and pipeline imports to UK's overall natural gas demand.

Equation:

$$y_{shale} = y_g - (y_i + y_p)$$

Commodity prices

EUA price calculation method

Due to the immense fluctuations in the EUA prices in the past, estimating a future price of the EUAs has proven to be extremely difficult. This study bases its future estimates on a prediction made by the CCC (2009) that EUA price will be around €22 in the year 2020. For the consistency, this price is also used in the time period 2021 – 2030.

Calculation method:

Future prediction was constructed on the bases of continual increase of EUA prices until the year 2020, when it is forecasted to reach €22 /tCO_2e (CCC, 2009).

In the year 2013, EUA price equaled to € 6 /tCO_2e, Prediction says that expected price of the EUA in the year 2020 will be €22 /tCO_2e. This study uses fixed, historical exchange rate between British Pound and Euro of £0.85 = €1

Equation:

$$y_{eua_n} = \left(z_a + \frac{z_b - z_a}{x_8 - x_a} * x_n\right) * q$$

2013 - 2020

y_{eua} = value for the year x_n (£/tCO_2e)
x_n= time vector (year 2013 = 1 = x_1 Year 2014 = 2 = x_2 …)
z_a = EUA price in the year 2013
z_b = EUA price in the year 2020
q = fixed historical exchange rate £0,85 = €1

In the time period 2020 – 2030 price has been kept on the level of 18.7 £ / t CO_2e

Natural gas price calculation method

For the estimation of the future prices of the natural gas, data acquired form the GOV.UK (2013e) providing natural gas wholesale prices have been used. Based on this data, statistical estimation of the future prices has been made. In addition to the statistical approach, predictions made by GOV.UK (2013e) have been taken into consideration. Same as the prediction of the UK's conventional gas production, the "official" natural gas price prediction has been found rather optimistic than realistic. In the further calculations, this study uses combination of both previously mentioned.

Calculation method:

First, prediction made by (GOV.UK, 2013e) has been taken into account.

Production in the year 2012 (p/KWh) = 2.09 (y_{gasa1})
Production in the year 2013 (p/KWh) = 2.34 (y_{gasa2})
...
Production in the year 2029 (p/KWh) = 2.45 (y_{gasa18})
Production in the year 2030 (p/KWh) = 2.45 (y_{gasa19})

Second, due to the fact that this study considers GOV.UK (2013e) prediction rather optimistic than realistic, statistical approach to estimate the future production has been applied.

Equation:

$$y_{gasb_n} = 0.0995 * x_n + 0.7521$$

y_{gasb} = value for the year x_n (p/KWh)
x_n= time vector (year 2001 = 1 = x_1, year 2030 = 2 = x_2 …)

Finally, because GOV.UK (2013e) prediction has been found too optimistic on one hand, and results of the statistical approach were suggesting unrealistically high prices of the UK's gas on the other hand, this study uses averaged values of the two previously mentioned.

$$y_{gas} = \frac{y_{gasa} + y_{gasb}}{2}$$

RESULTS / DISCUSSION

Electricity generation sector

In order to estimate the future natural gas demand in the UK's electricity generation sector, this study used fuel inputs into electricity generation data provided by GOV.UK (2013a). Fuel inputs provided by coal, oil, wind, nuclear power, hydroelectricity and other electricity sources were estimated. Figures 3 – 8 represent estimated future development of fuel inputs into electricity generation provided by above listed means of electricity generation. Further, future fuel inputs into electricity generation demand has been estimated, results are expressed by figure 9. Figure 10 represents a mere combination of all the above mentioned. The gap between estimated fuel inputs into electricity generation demand and supply provided by coal, oil, wind, nuclear power, hydroelectricity and other electricity sources expresses the estimated amount of natural gas necessary for electricity generation.

From the figure 9 it can be seen that traditional high-carbon means of electricity generation (coal, oil) will basically cease to exist as we know them now in next decade or so. This prediction is in consensus with the finding of Odeh, et al., (2007). On the other hand, renewables such as wind, hydroelectricity and "other" are expected to grow substantially which supports conclusions made by Department of energy & climate change (2011) and Sinded, G., (2005). Overall demand for fuel inputs into electricity generation is estimated to remain more or less constant in the future, or grow just slightly, even in this case, the results of this study correlate with the prediction made by Department of energy & climate change (2011). Figure 10 further shows that amount of natural gas used in electricity generation is expected to grow significantly in the years to come and to continue doing so till the mid-2020's when the full scale nuclear power generation is supposed to kick in. Research conducted by Grubb et al., (2005) and Stern, J., (2004) presents the similar results.

It is necessary to mention that this research uses high levels of estimated future generating capacities in the case of wind and nuclear power and expresses its changes momentarily rather than gradually. Significant year-to-year changes presented by this research are more likely to happen more gradually during several years rather than from a year to year. This fact does not compromise the integrity of this study, because the aim of this research is to capture long-term trends (which are not influenced by distribution of increase or decrease in generating capacity), rather than try to estimate the exact future values of each particular variable.

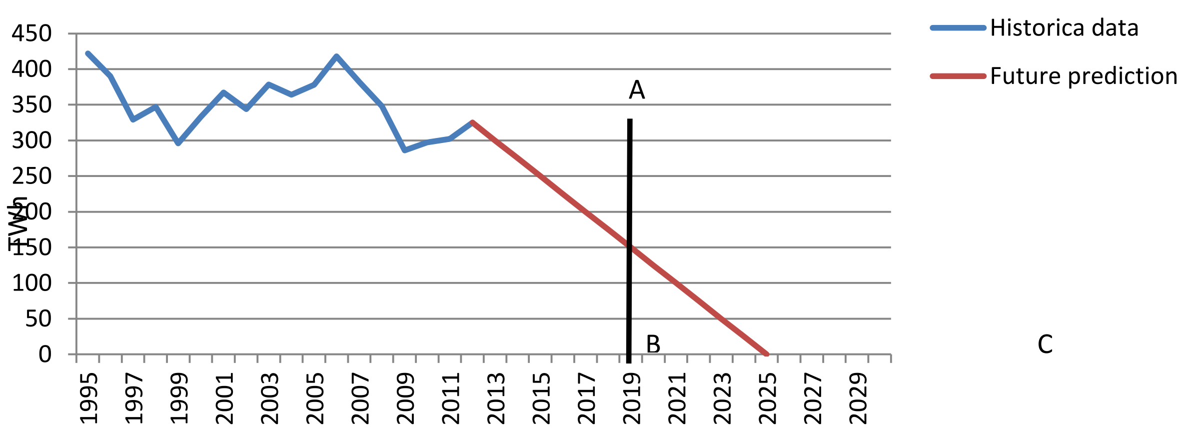

Figure 3: **Coal fuel inputs into electricity generation TWh-year**

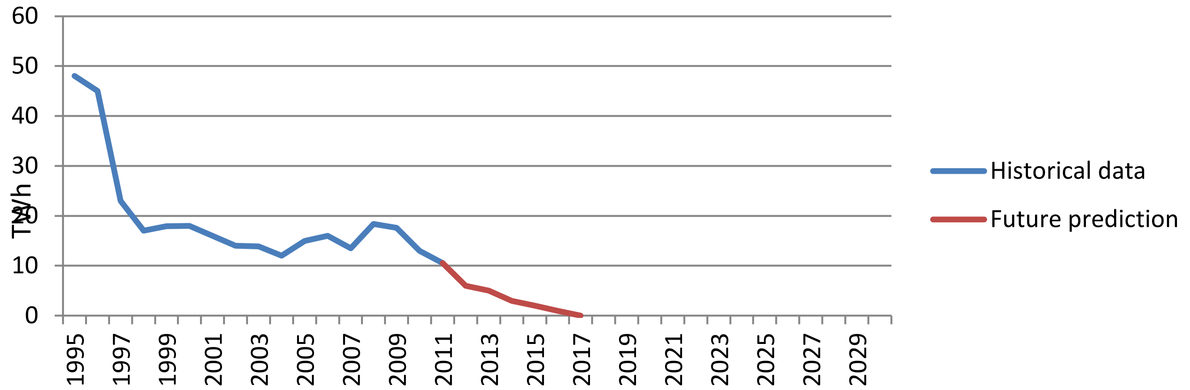

Figure 4: **Oil fuel inputs into electricity generation TWh-year**

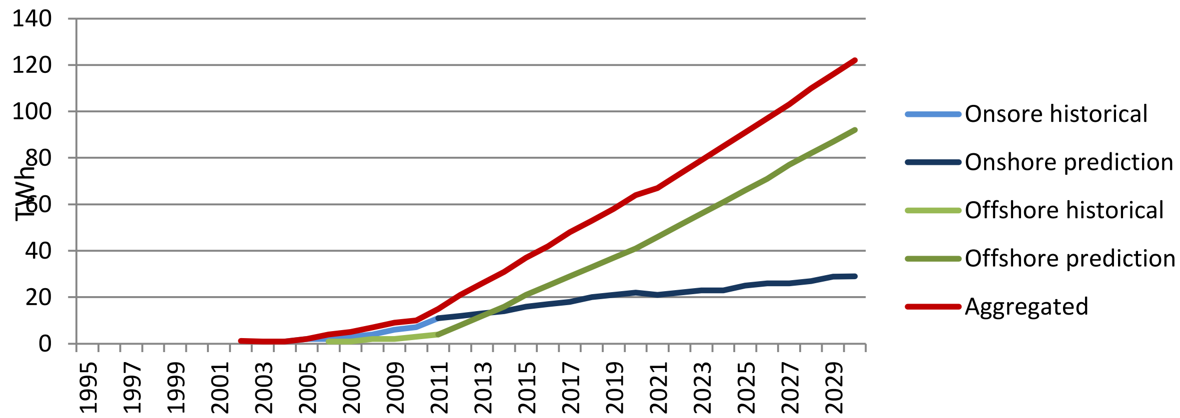

Figure 5: **Wind fuel inputs into electricity generation TWh-year**

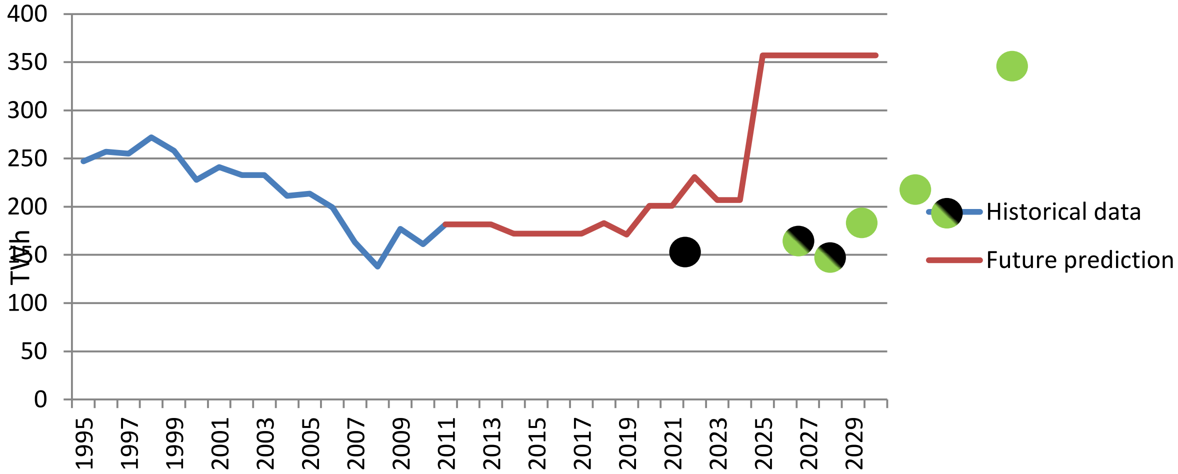

Figure 6: **Nuclear fuel inputs into electricity generation TWh-year**

Note: ⬤ *= old plant decommissioned*

⬤ *= new plant commissioned*

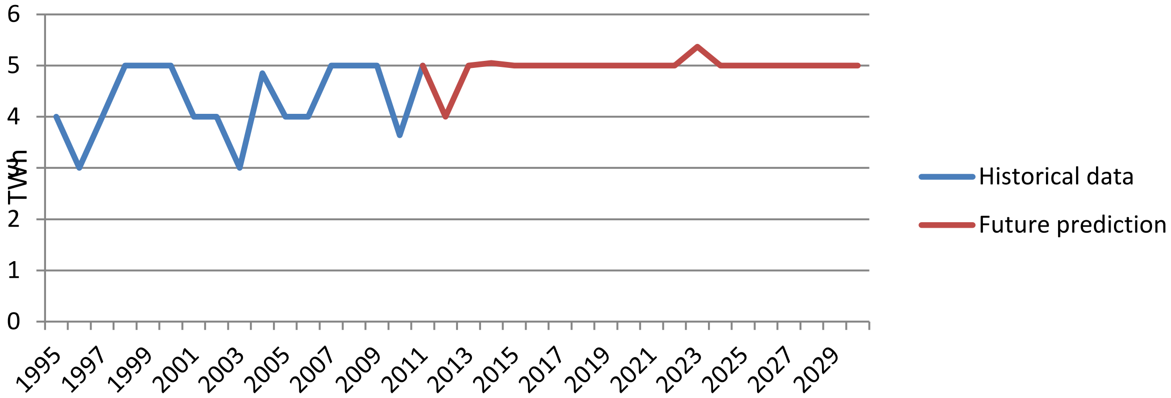

Figure 7: **Hydroelectric fuel inputs into electricity generation TWh-year**

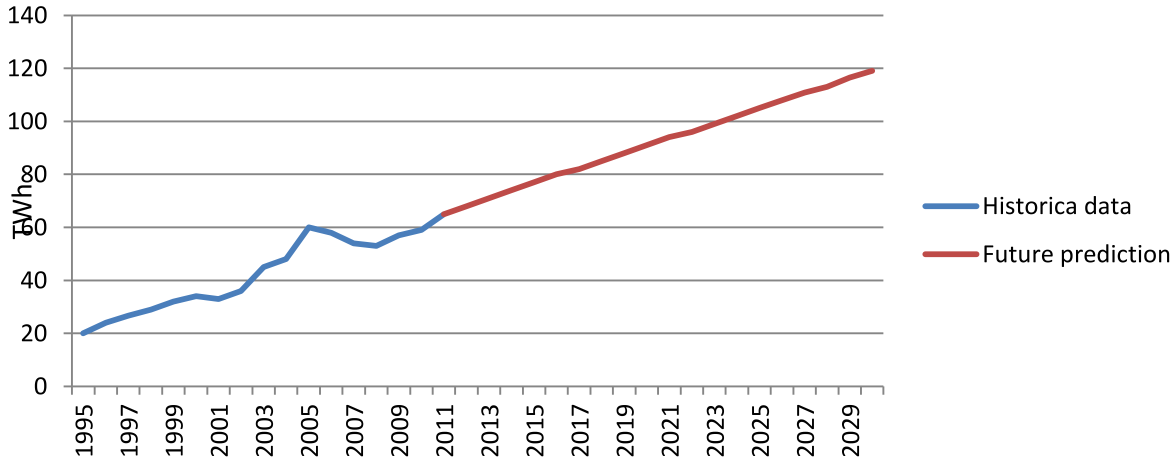

Figure 8: **Other fuel inputs into electricity generation TWh-year**

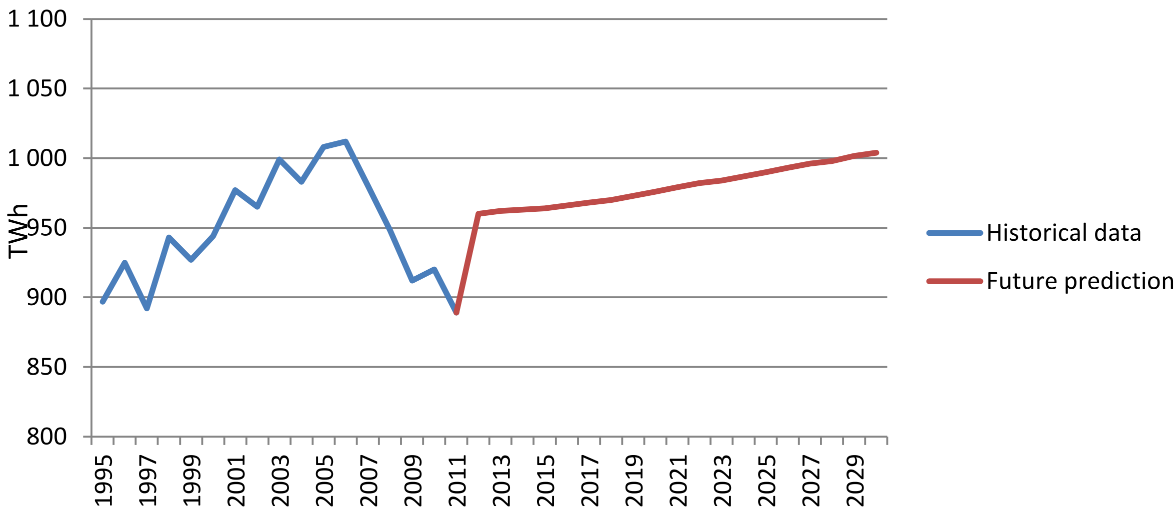

Figure 9: **UK overall fuel inputs into electricity generation demand TWh-year**

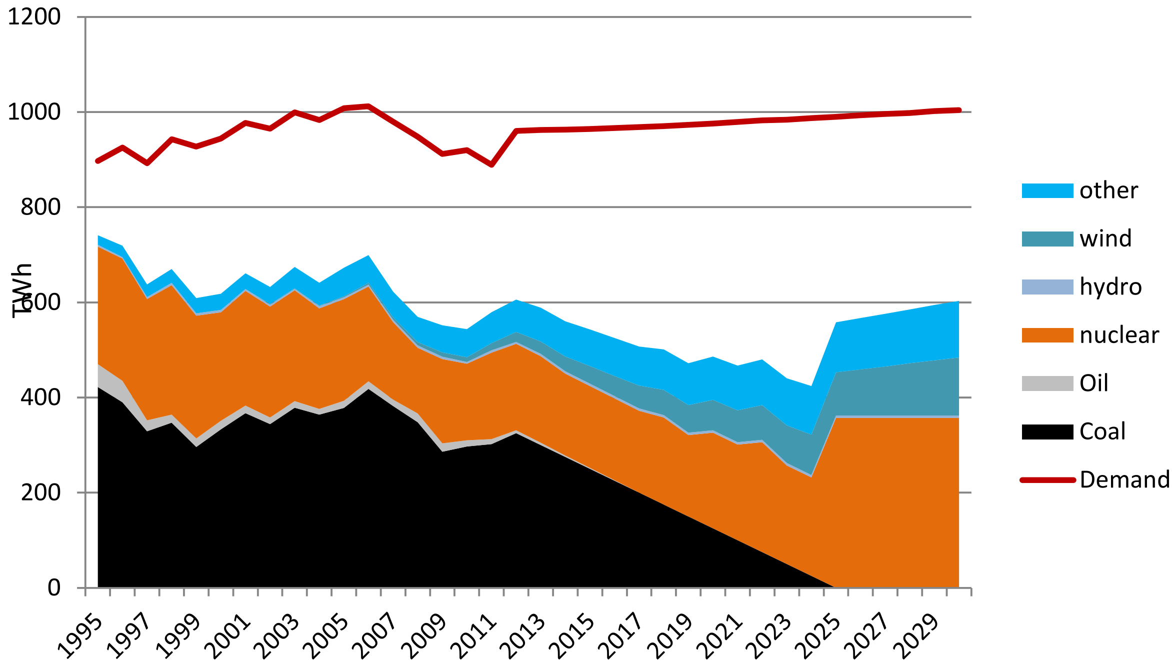

Figure 10: **UK's fuel inputs into electricity generation mix TWh-year**

Overall natural gas demand

Since the above described natural gas demand for electricity generation forms only a part of the overall natural gas demand in the UK. Broader natural gas demand has been estimated using data provided by GOV.UK 2013b. This demand represents amounts of natural gas used for transport, heating, and other industrial use. As can be seen form the figure 11, in the past predominant broader natural gas demand follows opposite trend than the demand for natural gas in the electricity generation sector. Even though in the mid 1990's it formed over 85 % of overall natural gas demand, it is expected to gradually decline to 50% of overall natural gas demand or even lower. Due to the decrease of the broader natural gas demand and increase of the demand for natural gas in the electricity generation sector, overall natural gas demand in the UK is expected hover at approximately same level till the mid 2020's when it will start to slowly decline when new nuclear power plants will have kicked in.

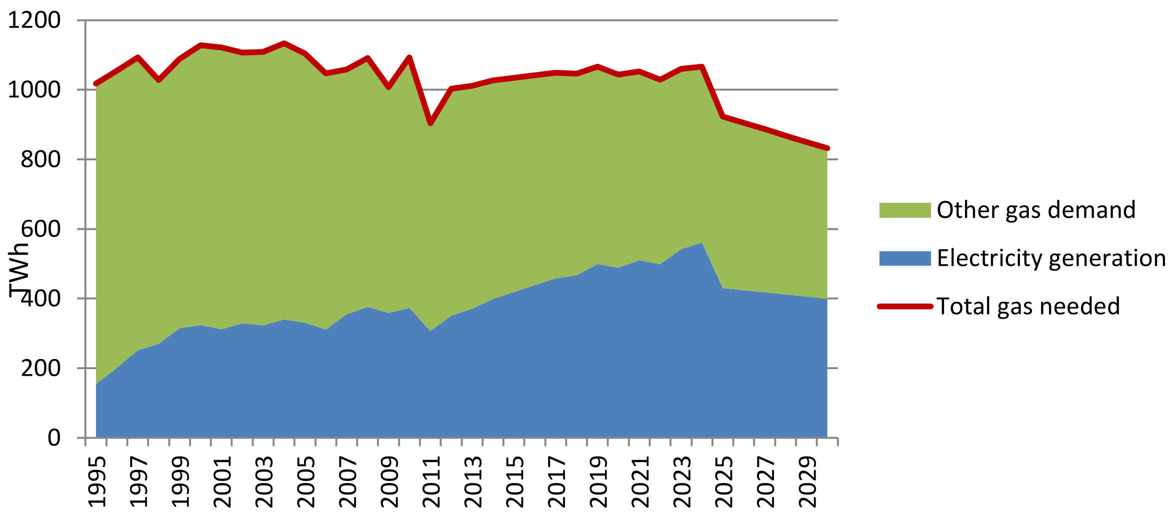

Figure 11: Overall natural gas demand in the UK TWh-year

Natural gas supply

When the future natural gas demand has been estimated, its composition has been closely examined. Model developed by this study uses data provided by GOV.UK (2013c). Figure 12 shows that UK conventional production is going to continue to decline but combination of statistical approach with the prediction made by UKCS (2013) suggests that its rate of decline will decrease in the years to come. Similar trend is predicted by the majority of the academic literature (Kong Chyong Chi et al., 2008, UKCS, 2013).

As the conventional natural gas production declines (figure 12) and overall natural gas demand remains stable or is expected to start to decline no sooner than in the next decade and a half or so (figure 11), natural gas imports are forced to grow significantly. Figure 13 represents estimated future natural gas pipeline imports. These imports are expected to grow rapidly as a reaction to the decline of conventional production.

Even though there are five pipelines supplying the UK with natural gas, it was not crucial for this study to try and distinguish between these pipelines and amounts of gas each of them is going to deliver to the UK. This research uses their aggregated capacities and supplied amounts under the designation “pipeline imports”. Further, it is important to mention that, to the best knowledge of the author, there is no academic literature focusing solely on natural gas pipeline imports to the UK (even though various studies addressing natural gas imports into the UK exist, focus on pipeline imports in particular is missing). Thus this prediction is merely of a statistical character.

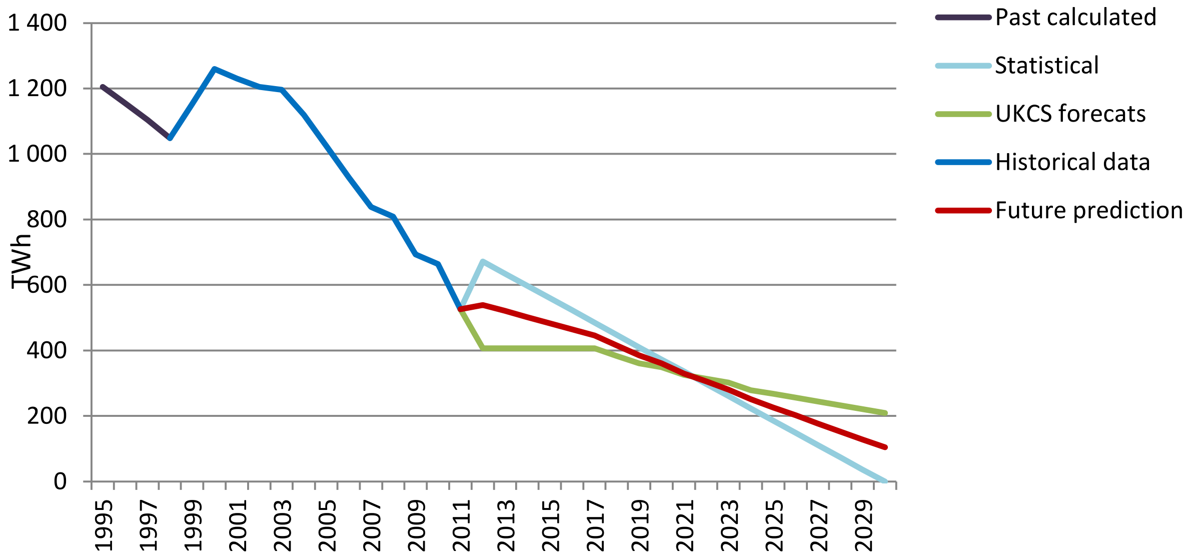

Figure 12: **UK conventional production TWh-year**

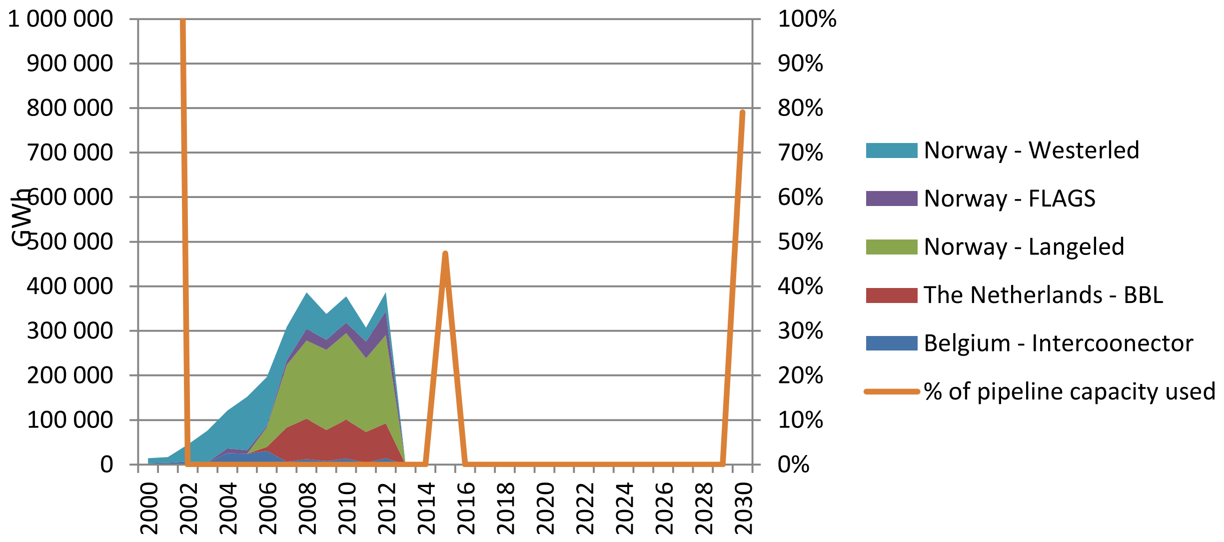

Figure 13: **Pipelines imports into the UK TWh-year**

Commodity prices

In order to carry the final economic analysis, future EUA prices and future price of the natural gas itself were estimated. Even though fluctuating greatly in the past, EUA prices are expected to more or less stabilize on the level around £18/tCO_2e. This conclusion has been drawn from CCC (2009) prediction and other circumstances such as intentions of Australia to join EU ETS and higher environmental concerns in the future (figure 14). Combination of statistical approach and prediction made by GOV 2013e suggests that natural gas prices are going to grow in the future but the growth is not expected to be any dramatic. Downward pressure put on the price by future oversupply of LNG is going to be balanced by natural tendency of natural gas prices to grow (Stevens, P., 2012) (figure 15)

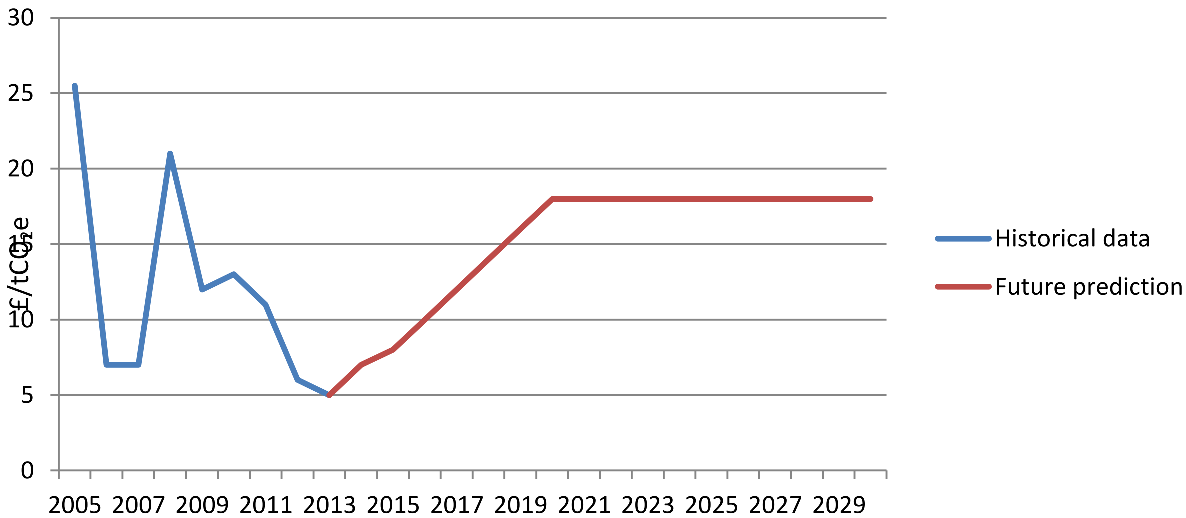

Figure 14: **EUA prices £/tCO_2e**

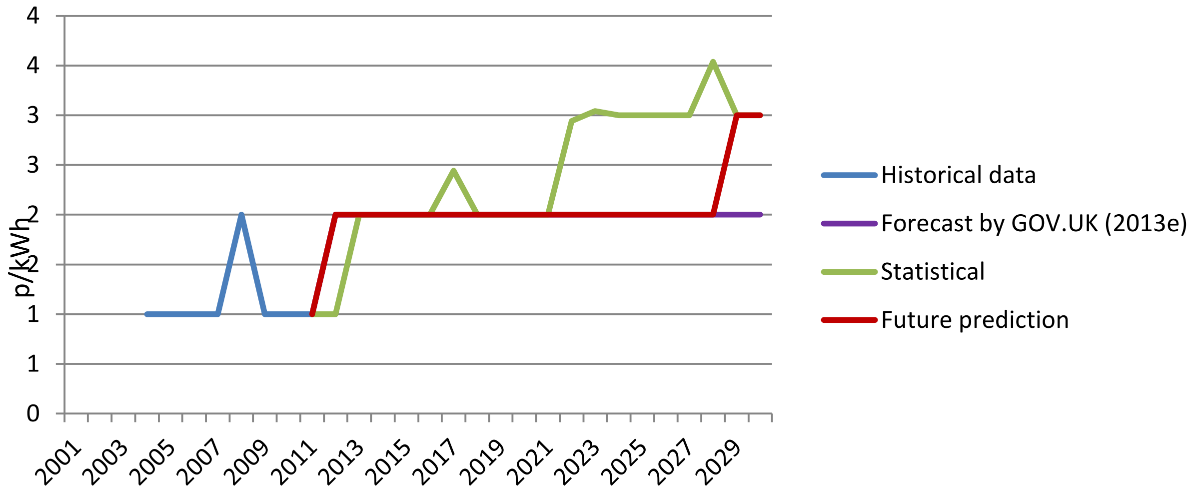

Figure 15: **Wholesale natural gas prices p/kWh**

UK natural gas mix

Blend of the UK's natural gas mix proposed by this study has been developed on the carbon emission bases to achieve the least polluting composition possible. In practice this means that sources of the gas were given a priority based on their emissions, using emission factors developed by Cranfield University (2013). The cited study ranks the natural gas sources according to their emissions in order: conventional production; pipeline imports (conventional gas) shale gas; LNG (any form), named in order form the least to the most polluting.

When the amounts which can possibly be supplied by the UK's conventional production and pipeline imports were compared with the estimated overall natural gas demand, a gap has been identified. This gasp can be filled by either UK's indigenous shale gas or LNG imports from overseas.

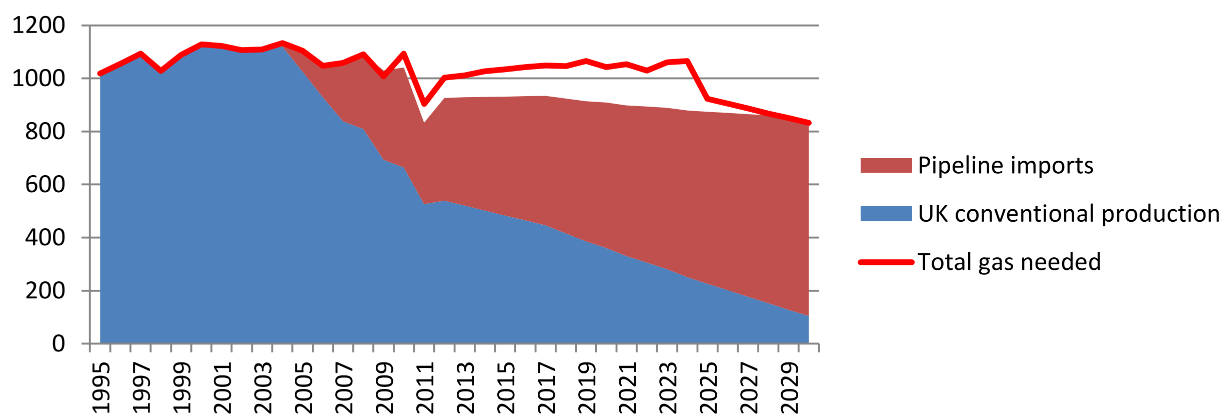

Figure 16: **Proposed natural gas blend**

In the time period 2014 – 2030, the previously mentioned gap between natural gas demand and supply ranges from 96 TWh in the year 2014 through its maximum of 183 TWh in the year 2024, when it is presumed to start to drop as new nuclear power plants kick in and amount of natural gas necessary for electricity generation drops.

Starting to count since 2014, this gap is worth 1582 TWh of natural gas which will have to be supplied by either shale gas or LNG. Case study 1 describes environmental and consequent monetary impacts of both previously mentioned possibilities. Case study 2 focuses on the LNG imports since the year 2005 until the year 2013.

Case study 1

Since it has been established that indigenous shale gas production has lower emissions than LNG, this case study has been conducted in order to more closely express difference between carbon and monetary costs of use of shale gas compared to the costs of the use of LNG during the time period 2014 - 2030.

Model represented by figure16 shows need for 1582 TWh worth of natural gas in the time period 2014 – 2030. This study uses emission factors developed by Cranfield University (2013): onshore LNG: 0.062; offshore LNG: 0.064; shale gas: 0.057 kg CO_2/kWh (transport emissions not included), and future commodity prices estimated by this study to assess environmental impacts of filling this gap by either shale gas or LNG.

In the case the UK indigenous shale gas would be applied, emissions produced by doing so would reach 89.5 million tons of CO_2e. If the current trends were to prevail and this amount of natural gas was to be supplied as LNG, this would result in emissions of 97.3 million tons in the case of conventional onshore LNG, 101.3 million tons in the case of conventional offshore LNG and 121.6 million tons of CO_2e in the case of LNG made out of shale gas extracted overseas. (7.8, 11.7 and 32 million tons more)

Expressed in monetary terms using natural gas and EUA prices estimated by this study, this translates into £124, £190 and £510 million pounds expressed in carbon costs only. In other words, introduction of shale gas into the UK's natural gas mix may save the UK or even the EU anything between £124 and £510 million calculated in the carbon tradable permits only, by the year 2030.

Figure 17: Shale gas extraction tower, *source: food & water europe (2012)*

Case study 2

This study examines carbon footprint of the LNG imports during the time period 2005 – 2012 compared to the carbon footprint which would have been left behind if the same amount of natural gas would have been supplied by the UK's indigenous shale gas. Purpose of this case study is to underline the fact that delaying the shale production in the past may have already caused monetary losses possibly unredeemable by the future actions.

Since the year 2005 when the first considerable LNG imports started, the UK has imported over 800 TWh of natural gas in form of LNG. The 800 TWh of gas imported as LNG caused GHG emissions of (presuming that the imported LNG was 50/50 mix of conventional onshore and conventional offshore gas) of 50 million tons of CO_2e (transport emissions not included). If the same amount of natural gas was sourced using the UK's indigenous shale gas, emissions crated this way would reach “only” 45 million tons of CO_2e. This is 5 million tons of CO_2e less than when LNG is used. Using EUA prices for each year since the LNG imports started and exact imported amounts from each particular year, this translates into extra costs of £55 million pounds only in the cost of extra carbon released into the atmosphere.

Figure 18: **LNG tanker,** *source: NMS2002 (2013)*

Outcomes of the introduction of shale gas into the UK's natural gas mix

From the research described above it is obvious that introduction of shale gas into the UK's natural gas mix may result in substantial emissions reduction and subsequently lead to monetary benefits. Millions of tons of CO_2e annually saved could help the UK to reach the environmental targets set for the years 2020 and 2030 (GOV.UK, 2013f). Even though these targets mostly address the use of renewable energy sources, which the shale gas is most certainly not, they also address the emissions reduction. This is where the shale gas could be of a great help.

Many may argue that even though UK's shale gas is more environmentally friendly than LNG imports, it is still much cheaper to source LNG from countries as Qatar or Algeria and use money saved this way for another form of environmental protection. To be able to more closely relate to the real monetary contributions of shale gas, it is important to determine the difference which those saved tones of CO_2e make in monetary terms compared to the actual price of natural gas. To determine this, carbon savings expressed in EUA (£/t) were compared to the actual natural gas prices (p/kWh). The results hover between virtually nothing and 3.5% of the actual natural gas price in each particular year, greatly depending on the EUA prices, origin of the natural gas the LNG is made of and price of the natural gas itself (figure 19).

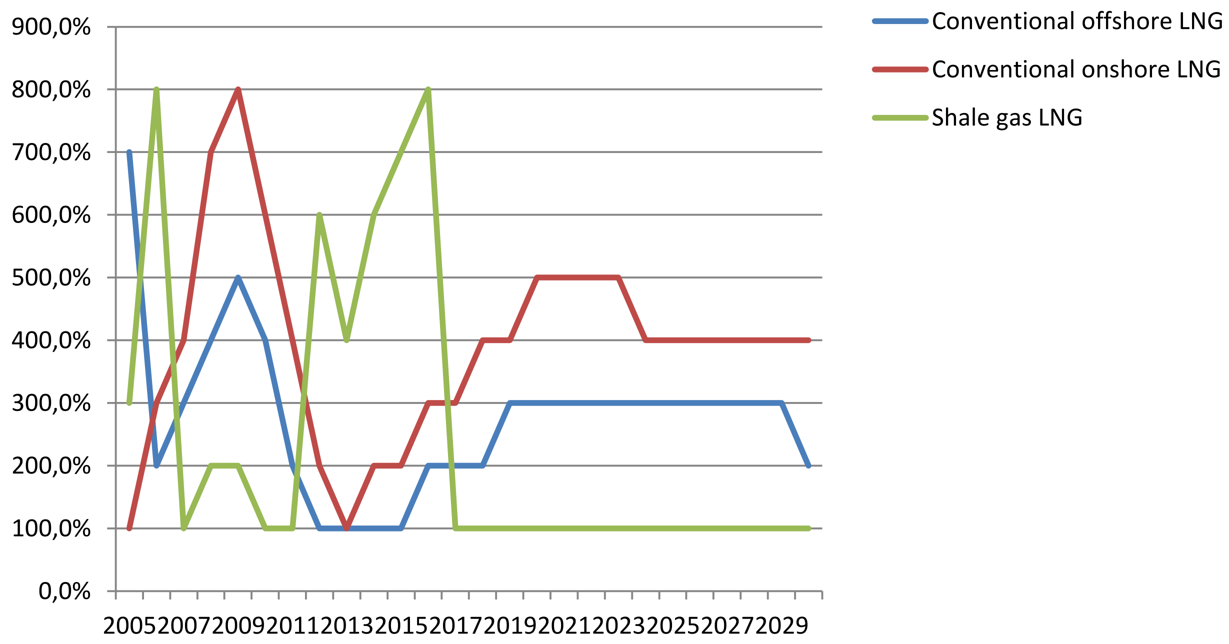

Figure 19: **Possible savings by using shale gas instead of LNG, expressed as a percentage of the gas price in each particular year.**

Using UK's indigenous shale gas instead of LNG would substantially decrease emissions caused by the use of natural gas and increase the UK's level of self-sufficiency in both natural gas production and electricity generation. In the past decade or so, the UK has moved from the role of net natural gas exporter to the role of net natural gas importer. This was caused mostly by the rapidly declining conventional production rather than growing indigenous demand. Results of this study suggest that even full-scale employing shale gas would not completely alter this situation but still bars a considerable improvement. UK indigenous shale gas may cover 20 – 30 % of the UK's natural gas demand for many decades to come.

Further, natural gas in general, and shale gas In particular, might provide a cheaper route towards low-carbon economy comparing to high-cost renewables (Stevens, P., 2012; Ridley, M., 2011). Natural gas may serve as a transition tool between high-carbon fossil fuels such as coal or oil towards zero-carbon technologies such as wind or nuclear and use shale gas instead of LNG would further decrease the carbon cost of natural gas use. Full deployment of renewable electricity sources would not have to mean the end of gas-fired electricity generation. Since the renewables such as wind or solar farms are highly unstable in their production rates (Siden, G., 2005), gas-fired power generation may still play a role of backup or peak electricity source even in the low-carbon economy.

CONCLUSION

Results of the first part of this study support prevailing opinion of Grubb et al., (2005), Stern, J., (2004) that the UK is going to face an energy crisis in a near future. Massive coal-fired power plants are being closed under directives such as LCPD and ILD, UK's nuclear power plant fleet is obsolete and most of the plants are about to be decommissioned in next decade or so, new ones are just in the phase of plan or a proposal. Renewable sources of electricity do not grow fast enough (even though considerably).

Further results of this study suggest that there is a growing gap between fuel inputs into electricity generation demand and supply, being filled with natural gas. These results are in full consensus with Grubb et al., (2005) and Stern, J., (2004). Increased natural gas demand for electricity generation, together with slowly decreasing, but still substantial broader natural gas demand (figure 11) puts even more pressure on the UK's natural gas conventional production, which is already not able to keep up with current natural gas demand. UK conventional production started to sharply decline in last decade and nothing suggests this trend is about to stop. Huge gap in the UK's natural gas supply created this way is being filled with imports of significant amounts of natural gas via pipelines and in form of LNG. Whereas the first mentioned is a reasonably environmentally friendly way of acquiring natural gas, but the latter one, LNG, is quite opposite of that.

Second part of this study probes in detail into the UK's natural gas mix, exploring options how to reduce carbon emissions related to natural gas in the UK and by doing so, help the UK to achieve the environmental targets set for years 2020 and 2030.

By the economic analysis carried as a part of this study, and on the example of two case studies, it has been suggested that use of the UK's shale gas instead of LNG, would lead to carbon savings of 7.8 to 32 million tons of CO_2e, which translates into anything between £124 and £510 million by the year 2030. Use of shale gas in the past, since the year 2005, would mean carbon savings of at least 5 million tons of CO_2e and subsequent monetary savings of £55 million in EUA permits only.

This study strongly suggests that, at least at the current stage of extracting methods and technology, shale gas is less polluting source of natural gas than any form of LNG. As natural gas in general is going to be a tool helping the UK in the transition period towards renewable sources of energy, replacing LNG with UK's indigenous shale gas production can help lower the carbon emissions of this transition era even more and help the UK to reach the environmental targets in the year 2020 and 2030.

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