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Briefing: Shale Gas and the UK's Low Carbon Transition

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Overview

The UK is undergoing a decarbonisation transition that will transform every sector of its economy. This report explores how shale gas could fit into this transition by examining the international and domestic context of climate change; the greenhouse gas intensity of shale gas from 'cradle to grave' ; the major uncertainties that need to be addressed in this area; and the potential whole-economy implications of shale gas deployment in the UK from a climate change perspective.

In brief, shale gas is thought to have a lower carbon footprint than some other fossil fuels (including coal and LNG). However, the need for extremely rapid decarbonisation leaves a relatively short and narrow window for its deployment without carbon capture if we are to meet our commitments to limit global warming to +1.5°C above pre-industrial levels. With carbon capture, it may have a major role in hydrogen production, but at consumption levels lower than today.

1 Introduction

The climate change implications of shale gas remain a highly contentious topic, not least due to much of the existing debate centring around the USA and its own experience of a shale gas 'boom' from the mid-2000s onwards. Proponents argue that the UK needs more natural gas as a 'transition fuel' as it decarbonises completely over the coming decades, and that a new domestic supply of gas could allow the UK to avoid importing higher-cost and higher-emission alternatives from abroad. Opponents argue that the emissions associated with shale gas are higher than one might assume and that our need to decarbonise immediately leaves no space for a new source of natural gas.

All of this discussion takes place at a time when the UK, like many other countries, is embarking on an all-encompassing transition to a lower carbon future amid increasingly obvious public concern and ever-tightening policy agreements. The latter include the legal obligation to meet 'net zero' greenhouse gas emissions by 2050 (BEIS, 2019c).

This report provides an overview of the implications of shale gas in the UK context, with a particular emphasis on the UK's efforts to mitigate climate change. It begins by outlining the context with relevant policies, laws and targets before discussing the carbon footprint of shale gas relative to other energy options. Finally, it addresses the potential whole-system implications of shale gas exploitation.

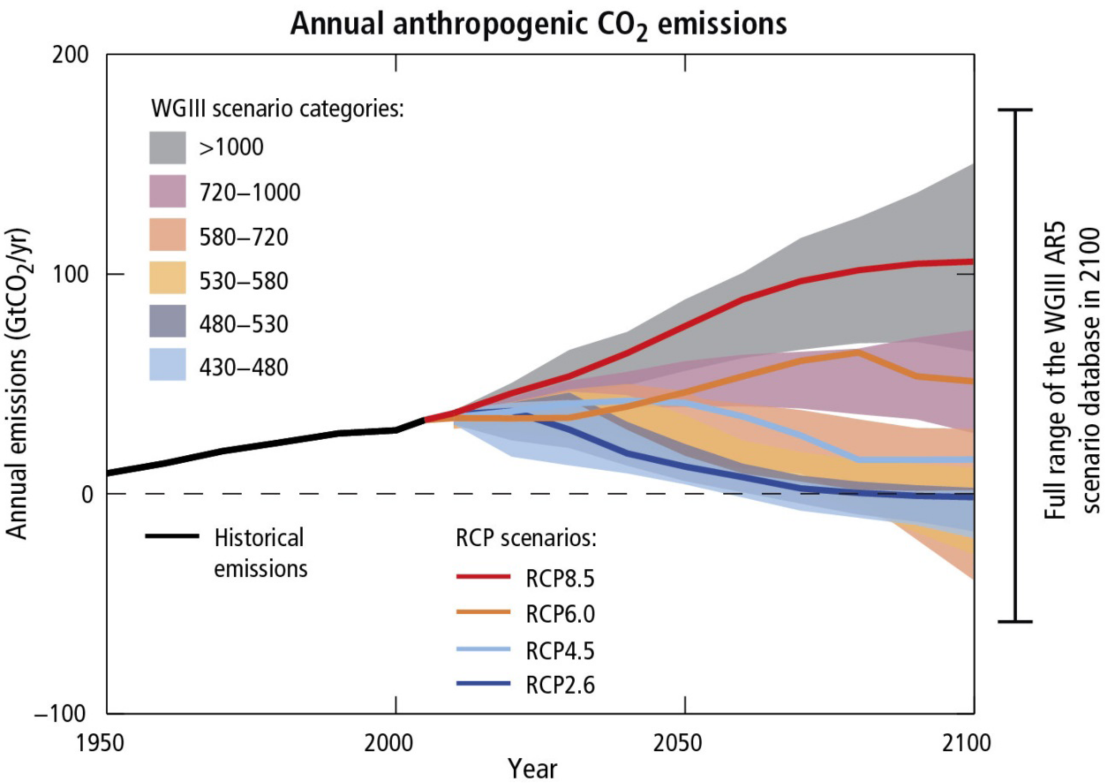

Figure 1 IPCC emissions scenarios to 2100 (IPCC, 2014) [WGIII: working group 3; RCP: representative concentration pathway]

2 Decarbonisation: Global Context, the UK and the Energy Sector

The international community has seen increasingly widespread policy agreement regarding climate change over the last three decades: since 1992, the UNFCC (United Nations Framework Convention on Climate Change) has generated various treaties and agreements, notably the Kyoto Protocol (adopted in 1997, signed by 84 states in 1999) and the Paris Agreement (adopted in 2015, signed by 195 states in 2016).

The latter of these has a goal of **limiting the global average temperature increase to a maximum of 2°C above pre-industrial levels, with an ambition to stay below 1.5°C.** Signatories of the Paris Agreement set their own emissions reduction targets ('nationally determined contributions'). These cannot be enforced by international law but nevertheless set a policy framework and international context for national pledges and laws.

The basis of these endeavours is consolidated and summarised by the IPCC (Intergovernmental Panel on Climate Change), whose role is to assess the science related to climate change in order to better enable evidence-based policy making. The most recent series of assessment reports was released in 2013-2014 (IPCC, 2014) and is due to be updated in 2022. The 2014 report envisaged a range of potential emissions scenarios, shown in Figure 1, using historical emissions data to project a variety of future paths. Based on the most current (in 2014) data on the climate impacts of GHGs, the four scenarios shown in Figure 1 would result in temperature rises of up to approximately +5°C compared to the climate of the late 1800s.

Of these, **the only scenario that is assessed as 'unlikely to exceed 2°C' by 2100 is RCP2.6**. The next most stringent scenario, RCP4.5, is 'more likely than not to exceed 2°C'. In the worst case – RCP8.5 – the year 2100 would see temperature increases possibly exceeding +5°C with sea levels rising by up to 1 metre.

It should also be noted that these scenarios only include CO_2 emissions. The continued emission of other GHGs, many of which are more potent than CO_2 in their greenhouse effect, means that the outcomes discussed above are conservative (see section 3.1 for more detail on the relative impact of different GHGs).

Consequently, **any genuine attempt to achieve the goals of the Paris Agreement (temperature rise of <2°C, preferably <1.5°C) must, at the very least, not exceed the emissions of scenario RCP2.6**. Given the fact that climate change is a cumulative emissions problem and that GHGs persist in the atmosphere for long time periods, this means that annual emissions must fall rapidly: as shown Figure 1, for RCP2.6, global CO2 emissions must start to decline by around 2025 and certainly by the late 2030s. **If the world is to achieve a maximum warming of +1.5°C rather than +2°C, global emissions must peak in the early 2020s and reach approximately zero by 2050**; only 30 years away (IPCC, 2018). The inertia of the world's economic and social systems makes this extremely challenging, and the extent of this challenge seems poorly comprehended by most governmental, industrial and public actors: **currently the climate change commitments of all countries around the world are thought to leave roughly 50% chance of exceeding +3°C warming by 2100** (Committee on Climate Change, 2019c). This is particularly concerning given insights generated by recent work, suggesting that the **Earth could be at significant risk of 'tipping cascades' i.e. runaway climate change at a threshold of only +2°C warming** (Steffen et al., 2018).

To place this in a European context, one recent study stated that:

"To meet its Paris 2°C commitment the EU needs over 12% p.a. mitigation, starting immediately."

(Anderson and Broderick, 2017)

However, it should be noted that the above study omitted the use of negative emissions technologies (such as biomass with carbon capture and storage) and subsequently arrived at a more aggressive mitigation conclusion than many other works.

2.1 Decarbonisation in the UK

The UK contributes approximately 1% of annual global GHG emissions (CAIT Climate Data Explorer, 2019), but is responsible for about 4% of cumulative historic emissions since 1850 (Gütschow et al., 2019). Moreover, its global political and cultural influence are considerable, creating further moral imperatives for action on climate change.

It is against this backdrop that the UK became one of the first countries in the world to impose on itself a legally-binding carbon emissions reduction target: introduced in 2008, the Climate Change Act obliges the UK to reduce its emissions by 80% by 2050, relative to a 1990 baseline (Climate Change Act 2008). In June 2019 this law was amended to a 100% reduction, i.e. **net zero emissions across the entire economy by 2050** (BEIS, 2019c). The UK is the first 'major' economy to create such a law.

This decarbonisation ambition is overseen by the Committee on Climate Change (CCC) which independently advises the UK government on meeting its target. To do this, the CCC provides country-wide carbon budgets, spanning five-year periods, which the UK is legally obliged to follow (Figure 2).

Thus far, official estimates show that the UK has stayed within its budgets for the 2008-2012 period (budget 3,018 Mt CO_2e, achieved 2,954) and the 2013-2017 period (budget 2,782 Mt CO_2e, achieved 2,503) (BEIS, 2019b).

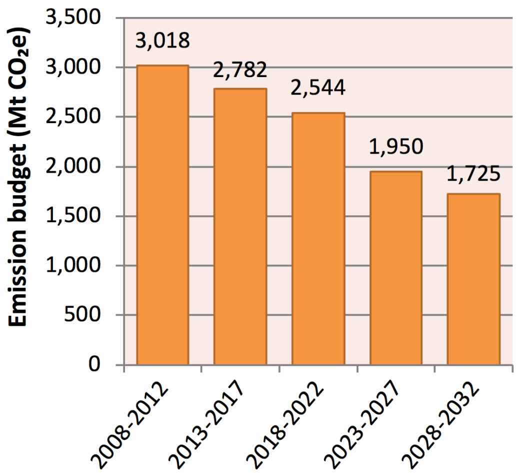

Figure 2 UK carbon budgets, as set by the Committee on Climate Change (Committee on Climate Change, 2019a)

However, as shown in Figure 2, the upcoming budgets become progressively tighter and will be harder to achieve: the CCC states that **the UK is currently off-track to achieve the fourth and fifth budgets shown in Figure 2** (Committee on Climate Change, 2019c). Worse, these budgets will need to be adjusted downwards in line with the new requirement for 'net zero' emissions by 2050.

2.2 The UK Energy Sector

Historically, the energy sector has been the greatest contributor to the UK's GHG emissions. This is in line with the rest of the world, for which energy supply accounts for around 35% of global emissions, even excluding the use of fuels by other sectors (IPCC, 2014). However, in recent years the UK and several other countries have achieved considerable success in decarbonising the energy sector. This is reflected in Figure 3 which shows that the **emissions from the UK's energy supply fell by 59.5% between 1990 and 2017.** The same time period has seen a drop of only 12% in national energy demand, indicating that emissions intensity has approximately halved.

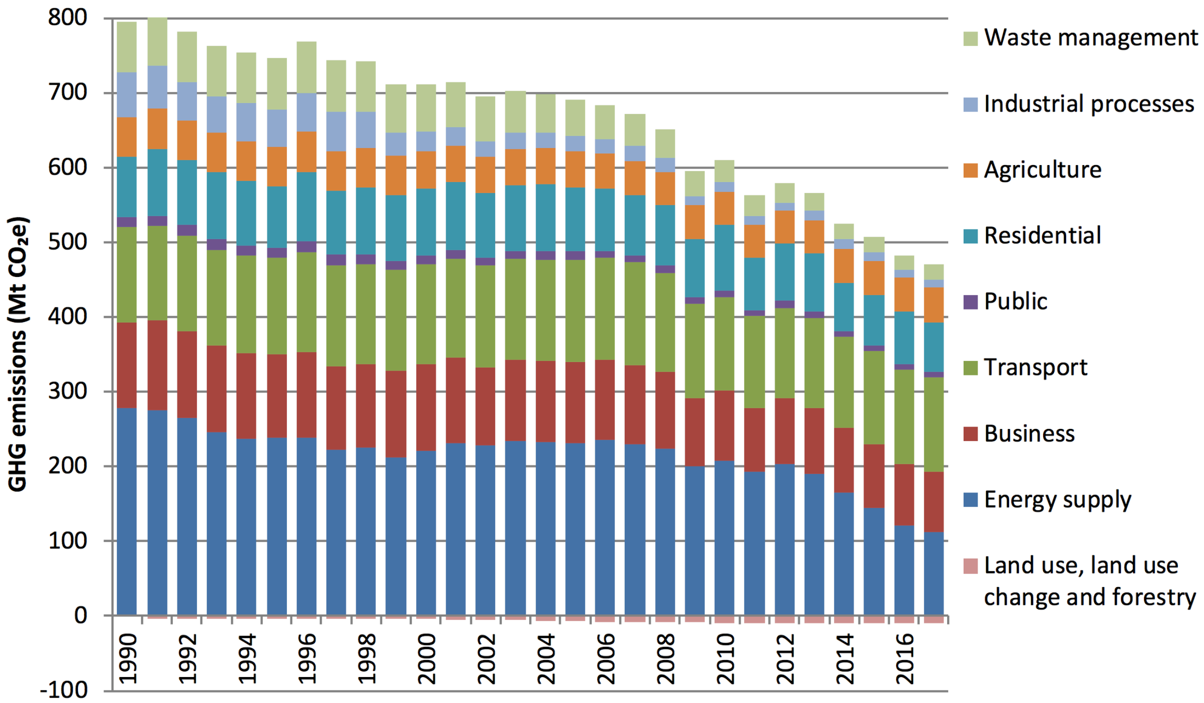

Figure 3 UK greenhouse gas emissions, by source, 1990-2017 (BEIS, 2019b)

Finally, it should be noted that, while energy supply accounted for 24% of 2017's GHG emissions (Figure 3), this only represents the supply side, e.g. extraction of fuels and operation of power plants. Much of the emissions from other categories — 'business' and 'residential' for instance — arise from the combustion of fuels to provide heat. Consequently the reach of the energy sector as a whole is far greater than the 24% of emissions shown here.

Figure 3 also demonstrates that the rate of decarbonisation of the energy sector has increased markedly over the last decade. This is primarily attributable to **the simultaneous decline of coal power and rise of renewables:** two phenomena that have occurred specifically in the electricity sector which has diversified extensively in recent years. This is illustrated by Figure 4, showing the transformation of the UK electricity generation mix over the last decade. As of 2018, 44% of electricity came from fossil fuels, 31% from renewables and 18% from nuclear power plants (BEIS, 2019a). While nuclear power's contribution has remained quite steady for the past ten years, fossil fuel generation has halved and renewable generation has increased by a factor of 5.

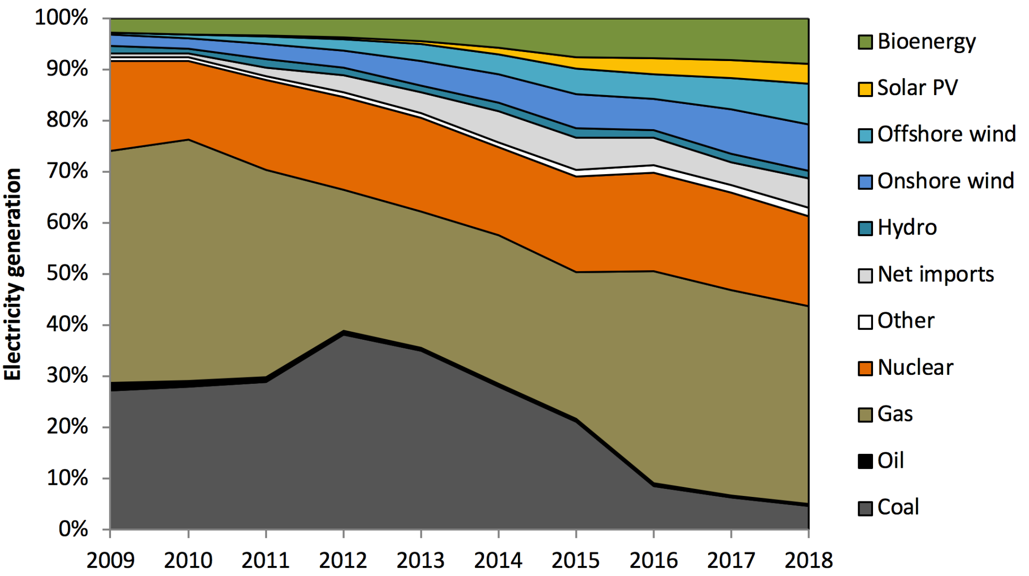

Figure 4 UK electricity mix (BEIS, 2019a)

However, despite the decline of fossil fuels in electricity generation, natural gas still supplies 39% of our electricity. Gas also accounts for the vast majority of domestic and industrial heat, and overall causes 35% of total national GHG emissions (BEIS, 2019b).

In total, the UK still consumes as much natural gas as it did in the mid-1990s, although it has begun to fall in recent years. However, the source of this gas has changed somewhat as the UK's North Sea reserves have continued to decline since peak output was reached in 2004. Norway has been the biggest supplier of natural gas to the UK for many years (see Figure 5), although an increasingly diverse and international **liquefied natural gas** (LNG) market has become a key source. This LNG supply was originally dominated by Qatar but is now arriving from a range of countries including Russia and the USA.

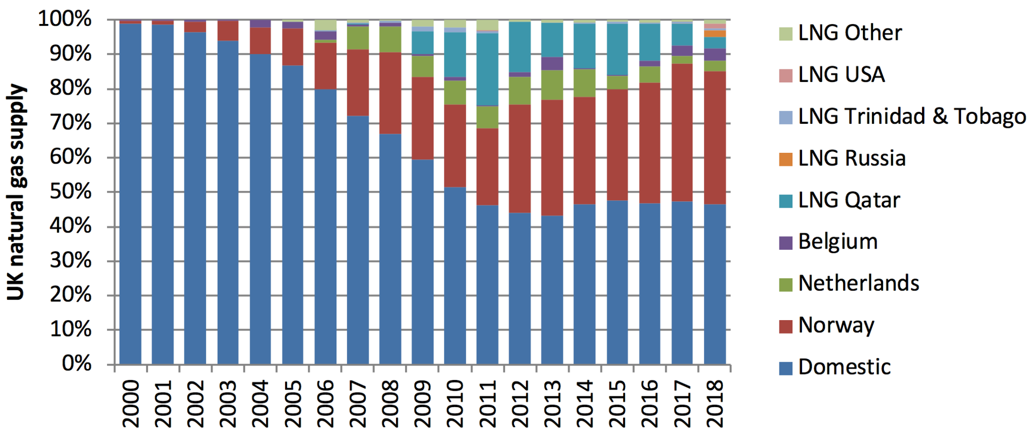

Figure 5 UK natural gas supply, 2000-2018 (BEIS, 2019a) [LNG: liquefied natural gas]

3 How GHG-intensive is Shale Gas?

The composition of shale gas is fundamentally no different to that of other sources of natural gas. Moreover, all gas – whether conventional, shale or otherwise – must meet strict composition standards before entering the National Transmission System. Therefore the emissions from the combustion of shale gas for heat or power are the same as those of conventional gas. However, differences lie in the rest of the life cycle. For this reason, the use of life cycle assessment (LCA) is critical in investigating the environmental impacts of shale gas and other energy sources.

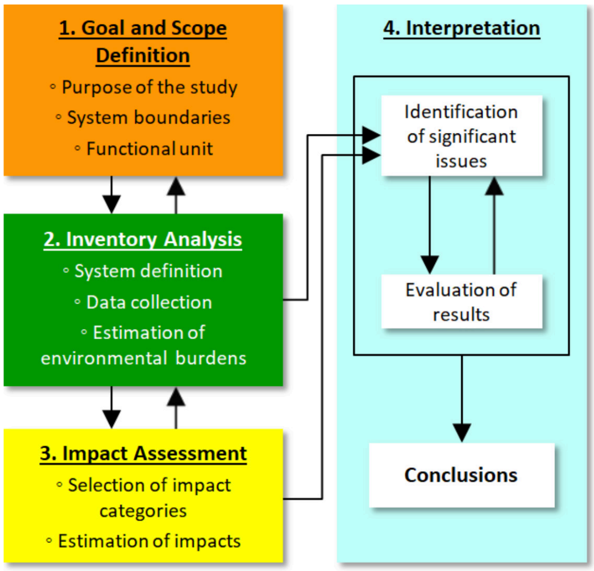

Figure 6 The four stages of life cycle assessment

3.1 Life Cycle Assessment

LCA is an ISO standardised technique (ISO, 2006a, ISO, 2006b) with well-developed methods and, in many cases, robust data sources. It works on the principle that **all resource consumption and emissions attributable to a product or process should be accounted for, from 'cradle-to-grave'** (or variants thereof, such as 'cradle-to-gate'). In other words, it accounts for environmental impacts from raw material extraction to processing, transport, waste management and any other relevant stages of a product's life cycle. This ensures that we do not cause unintended environmental impacts at less obvious parts of the life cycle by focusing solely on one stage. The general framework for LCA is shown in Figure 6, in line with ISO 14040/44 (ISO, 2006a, ISO, 2006b).

LCA covers a relatively broad range of applications and approaches, with carbon footprinting being only one. In a carbon footprinting exercise, once the system of study has been defined in the *Goal and Scope Definition stage*, the *Inventory Analysis* stage follows, comprising the calculation/estimation of all emissions of GHGs throughout the life cycle of the system.

Then, during *Impact Assessment*, each emission is multiplied by a factor describing its climate change potency relative to carbon dioxide: for instance, methane (CH_4) is approximately 34 times more powerful than CO_2 in terms of its greenhouse effect (IPCC, 2014). Typically these factors are based on the effect of each gas over a 'time horizon' of 100 years, but other options are possible and are discussed below. Finally, CO_2-equivalent (CO_2e) values are summed to give a total climate change impact.

The choice of time horizon is particularly important for the gas sector due to methane's short atmospheric lifespan of ~12 years compared to CO_2 which persists for centuries. The most common time horizons used in carbon footprinting are 20 and 100 years (although 500 years is also occasionally used when very long-term intergenerational equity is a focus). When a shorter period is considered, methane's effect is amplified: **over 20 years, CH_4 is 86 times as potent as CO_2** per kg emitted (IPCC, 2014). While 100 years is the default time horizon in LCA, some argue that 20 years is more appropriate for climate change given our short term goals and budgets. In such cases, leakages of natural gas throughout the life cycle are critical determinants of the climate change impact.

It should be noted that LCA is used to estimate not only carbon footprints: other environmental impacts such as acidification, eutrophication, photochemical smog creation, eco-toxicity, human toxicity, and others are often estimated simultaneously. However, these impacts are beyond the remit of this report: interested readers are referred to other publications such as those by Stamford and Azapagic (2014) and Cooper et al. (2014).

3.2 The Carbon Footprint of Shale Gas Electricity

A considerable body of literature has built up over the last 20 years applying LCA to a variety of energy sources. In the last decade, this has also included shale gas. Such assessments take into account the impacts of everything from the production and use of drilling fluid and fracking fluid to on-site emissions from diesel equipment and the well itself, flowback water treatment, gas processing and the transport of all goods required to and from the extraction site. Broadly speaking, while some similar conclusions can be drawn from these assessments, uncertainties remain and require further work. The findings of these LCAs are discussed below.

The majority of LCA work on shale gas has considered its use for electricity generation rather than other applications such as domestic or industrial heating. This is perhaps due to ease of comparison: contextualisation of an energy source's impacts requires direct comparators, of which electricity provides many but heat far fewer.

Two publications (Cooper et al., 2016, Hammond and O'Grady, 2017) reviewed 17 such studies. The outcomes are shown in Figure 7 for shale gas burned in a combined cycle gas turbine (CCGT)[1]. These studies found an **average carbon footprint of 503 g CO_2e/kWh of electricity**. Figure 7 also shows a variety of other electricity technologies based on data from a broad review conducted by the IPCC (Bruckner et al., 2014). This shows that conventional natural gas has a typical carbon footprint of 490 g CO_2e/kWh, **meaning shale gas is thought to be only a few percent worse than conventional gas** in terms of climate change.

However, compared to other options including those shown in Figure 7, **shale gas is only preferable to coal**. Most recent efforts to decarbonise energy systems around the world have focused on technologies such as solar, wind and nuclear which have footprints of around 45, 12 and 12 g CO_2e/kWh, respectively. **In this context, no existing or prospective fossil fuels are competitive** without carbon capture technologies.

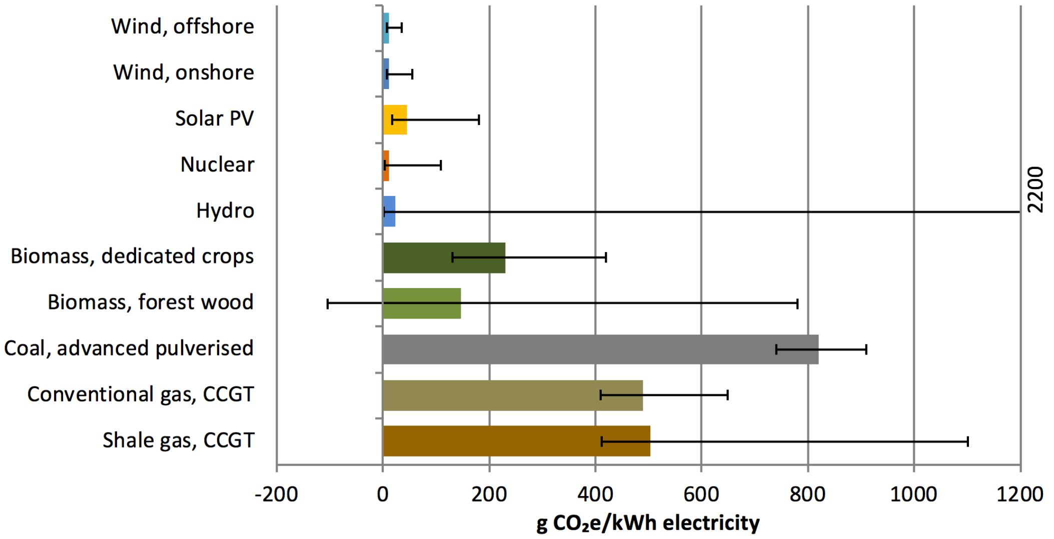

Figure 7 Carbon footprints of electricity generation technologies (Cooper et al., 2016, Bruckner et al., 2014) [PV: photovoltaics; CCGT: combined cycle gas turbine]

3.3 Shale Gas as a Substitute for LNG

As shown previously, in Figure 4, the past decade has seen an average of around 15% of the UK's gas supplied in the form of LNG, predominantly from Qatar. This is a relatively new addition to our gas supplies. LNG is liquefied at the LNG export terminal, which requires a considerable amount of energy, and is then regasified on arrival in the UK, again requiring energy. Further gas is typically consumed as fuel for the oceanic transportation in between, and more losses are incurred as boil-off and via leakages at terminals. Consequently LNG has a higher impact than pipeline gas.

Unfortunately there is relatively little robust data on the carbon footprint of LNG, particularly because it could vary considerably depending on its country of origin and the specific technologies used – for instance, the industry is currently developing electrified and renewably-powered liquefaction processes as it must attempt to reduce emissions to maintain future profitability (Stern, 2019). Based on typical liquefaction technologies, one estimate found LNG from Qatar to have a carbon footprint of approximately 508 g CO_2e/kWh (Stamford and Azapagic, 2014), while others estimated 494-547 g for the USA (Pace Global, 2015) and 562-666 CO2e/kWh for Canada (Kasumu et al., 2018). MacKay and Stone (2013) found that LNG's carbon footprint was approximately 10% higher than conventional gas, which is in line with the studies above.

1 CCGTs are used primarily for large-scale continuous power production and comprise 93% of the gas-fired capacity in the UK. Conversely, open cycle gas turbines (OCGTS) are less efficient, smaller generators used primarily for short periods at times when electricity demand is high (so-called 'peaking' plants).

Therefore **if the UK were to offset LNG imports with domestic shale gas supplies, a small saving in emissions would be likely**. The size of this saving is uncertain and depends on the origin of the LNG. It should also be noted that LNG may itself be shale gas: 2018 saw the UK's first imports of LNG from the USA, some of which would have originated from shale. This effectively combines the higher impacts of shale gas and LNG processes, likely resulting in a product with higher impacts than both. Therefore, if the proportion of shale gas in our LNG imports continues to increase, then the benefit of substituting these imports with domestic shale gas will also increase.

Supporting this idea, a comparison of three future gas supply mixes for the UK found that, on a life cycle basis, a mix dominated by domestic shale gas had lower emissions than mixes dominated by imported LNG or Russian gas, and that the saving increased over time (P. Hammond and O' Grady, 2017).

However, this argument has one major caveat: doubts remain about the net global emissions savings of substituting one fossil fuel for another, lower-carbon fossil fuel. The Jevons paradox and the Khazoom-Brookes postulate suggest that, if the UK imports less LNG as a result of domestic shale gas extraction, this decreased demand will cause a fall in global LNG prices leading to increased consumption elsewhere.

Some analysis of the US shale gas revolution corroborates this idea. The energy sector in the USA has seen an estimated emissions reduction of 14% since 2007 due to the replacement of coal power with gas, driven largely by the shale gas boom (U.S. Energy Information Administration, 2018). However, it appears that the resulting depressed coal market drove increased uptake elsewhere, negating around half of the USA's emissions savings (Broderick and Anderson, 2012). Other recent work has shown, similarly, that the global increase in natural gas demand has caused a rise in emissions despite its role in displacing coal, and this now threatens the Paris Agreement targets (Jackson et al., 2019).

LNG is slightly different to coal in that it is still a globalising market with regional pricing systems rather than a single, unified, marketplace. However, one might expect the same result in the case of shale gas versus LNG. Consequently, **the idea that UK shale gas will reduce global emissions by substituting imported LNG should be treated with caution**.

3.4 Carbon Capture and Future Electricity Scenarios

Carbon capture, utilisation and storage (CCUS) is often included in future energy scenarios to reduce emissions from fossil fuel energy sources and might provide a way to make shale gas combustion environmentally competitive. However, the CO_2 capture efficiency for a system burning natural gas is likely to be approx. 90% (IEAGHG, 2019) – i.e. 10% of CO_2 emissions are still released to the atmosphere – and this only applies to the power plant itself, leaving all upstream emissions such as fuel extraction, processing, etc., untouched. If these upstream emissions are accounted for, the effective overall capture rate is thought to be approximately 70% (Hammond et al., 2013).

On top of this, CCUS equipment itself requires some energy, leading to an additional energy loss of around 8% at the power plant (IEA, 2015): in other words, more gas would need to be burned to generate the same power output, leading to a rise in upstream emissions. **Therefore, CCUS might reduce the carbon footprint of a gas-fired CCGT from around 500 to 160 g CO2e/kWh**[2]. As shown by Figure 7, this is still an order of magnitude higher than many competitors, although it is competitive with biomass.

Moreover, we must bear in mind the UK's requirements for rapid decarbonisation, as outlined in section 2.1. Most analyses of future energy scenarios conclude that **electricity must be almost zero-carbon by the 2030s** to provide a realistic chance of meeting the UK's 'net zero' carbon target by 2050 (e.g. National Grid Electricity System Operator, 2019, McGlade et al., 2018). This will have to be reached in part by increased deployment of renewables such as wind and solar power, forcing thermal power plants to frequently ramp up and down to accommodate the variable output of the renewables; in other words, thermal plants will run at low capacity factors in future. This reduced output is likely to lead to lower revenues, making gas power even less economically attractive, with or without CCUS, and perhaps necessitating capacity payments or other support mechanisms depending on the state of electricity storage deployment.

In this context, **even when CCUS is used, the generation of electricity from fossil fuels must decrease markedly within the next 20 years**. Given the fact that CCUS is not yet economically viable and would naturally incur lead times of several years, the most viable role for CCUS in the UK's electricity sector might be with biomass, allowing negative net emissions.

2 A modern CCGT has direct plant emissions of ~380 g CO2e/kWh. Therefore ((380 ÷ 0.92) × 0.1) + (500-380) = 161 g/kWh.

Note that the above discussion refers primarily to electricity. Potential roles for gas, with and without CCUS, are likely to be greater in other parts of the economy, as outlined in Section 4.

3.5 Uncertainties and Unresolved Issues in the Carbon Footprint of Shale Gas

As shown by the error bars in Figure 7, the carbon footprint of shale gas appears to be more variable than that of conventional gas. Prior LCA work has shown that **the key parameter in determining its impact is the estimate ultimate recovery (EUR)** of the well, i.e. the total amount of gas extracted from the well over its lifespan (Cooper et al., 2014, Stamford and Azapagic, 2014, Costa et al., 2018, Laurenzi and Jersey, 2013). This is because much of the GHG emissions associated with extraction are somewhat fixed: for instance, producing drilling fluid and fracturing fluid, the drilling and fracturing operations themselves, completion of the well and potentially liquids unloading are all key sources of emissions that must be undertaken regardless of the total productivity of the well. If these high-emission activities do not lead to large volumes of gas, the carbon footprint per m^3 or MJ of gas will be higher.

Past experience has shown that the EUR of operating wells can vary enormously, leading to huge variation in the carbon footprint of gas from different wells. For this reason, some studies have recommended that on-site activities should be very limited until a reasonable EUR can be assured.

Other areas of uncertainty include total methane emissions. For the entire natural gas supply chain (conventional and unconventional), **methane emissions are generally thought to be 0.3–2.4% of the total produced methane** (Balcombe et al., 2015). However, direct measurement surveys conducted in recent years have tended to suggest that such estimates require revising upwards (see, e.g., Plant et al., 2019, Riddick et al., 2019). There are also uncertainties over the effects of 'super-emitters': small numbers of sites with extremely high emissions that are likely to skew the total average upwards.

Another challenge for LCA in this area is **the granularity of modelling of on-site activities**: often the emissions incorporated into LCA are generalised values rather than robustly characterised process-specific inventories. 'Nitrogen lifts' and other enhanced recovery techniques, for instance, have received virtually no attention in LCA literature, while end-of-life well emissions are poorly quantified.

Overall one would expect greater variability in the carbon footprint of shale gas in the USA than in the UK due to the UK's tighter regulatory regime – for instance the banning of flowback water reinjection – and uniform, nation-wide application as opposed to state-by-state variance (Hammond and O'Grady, 2017). However, this could only be proved by longer-term development in the UK yielding real-world data.

Finally, a critical issue receiving less attention in the fossil fuel sector is that of **land use change (LUC)**. Soils store carbon which, if disturbed through land clearance or other activities, can be released into the atmosphere as carbon dioxide and methane. One study estimated that the LUC impact of developing shale gas sites on grassland would be 1.21 g CO_2 eq. per MJ of gas, rising to 13.41 g CO_2 eq. per MJ if developed on peat land (Bond et al., 2014). This latter case was a particular concern for Scotland which has quite extensive peat coverage that requires protection.

4 How could Shale Gas fit within our Decarbonising Economy?

Much of the discussion above has addressed large-scale electricity generation, concluding that shale gas probably has a limited role to play. However, as shown in Figure 8, domestic and industrial heating are bigger sources of gas demand in the UK than electricity. So, might shale gas fit into future decarbonisation scenarios within the heat sector?

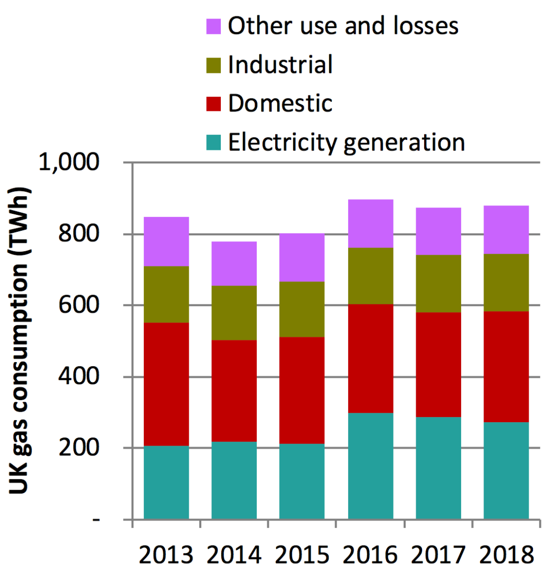

Figure 8 Natural gas consumption in the UK (BEIS, 2019a)

Much of the UK's heat demand is for low-temperature heat such as space- and water-heating: i.e. temperatures of 100°C or less. Therefore we might consider the impacts of common boiler systems.

Based on the LCA studies discussed above, the median **carbon footprint of shale gas per unit of energy content is approximately 67 g CO_2e/MJ** in a potential range of 56-161 g (Burnham et al., 2011, Howarth et al., 2011, Hultman et al., 2011, Jiang et al., 2011, MacKay and Stone, 2013, Dale et al., 2013, Cooper et al., 2014, Stamford and Azapagic, 2014, Tagliaferri et al., 2017, Costa et al., 2018). In other words, **burning shale gas in a boiler with 90% efficiency gives a carbon footprint of about 74 g CO_2e/MJ of heat** (= 67 ÷ 0.9).

In contrast, if we consider an air source heat pump with a coefficient of performance (COP) of 2 — a conservative assumption — then the equivalent carbon footprint would be approx. 37 g CO_2e/MJ of heat: half that of a gas boiler[3]. Consequently, at least in the provision of low-temperature heat for the domestic and industrial sector, **gas cannot compete with alternative heat options on carbon footprint**. It should be noted, however, that deployment of heat pumps faces some economic and social challenges which are currently the subject of ongoing research (Snape et al., 2015, Gross and Hanna, 2019).

Because of these GHG differences, most zero-carbon and low-carbon scenarios include widespread electrification of heat and/or the replacement of natural gas with hydrogen combustion: examples include National Grid's Net Zero scenario among others (National Grid Electricity System Operator, 2019). Even scenarios aiming for an 80% reduction in GHGs rather than net-zero typically conclude that **heating can use virtually no gas by 2050** (Dodds and McDowall, 2013, Ekins et al., 2013, Sustainable Energy Association, 2019). In the more immediate future, the newly developed **UK Future Homes Standard will ban gas heating in new homes from 2025** (MHCLG, 2019).

So, despite the strong inertia of the UK's old housing stock, **it is likely that residential natural gas demand will fall markedly in the next 20 years**.

However, while the direct use of gas will decline, **one area in which shale gas could play a greater, longer-term role is in the production of hydrogen for heating and transport**. This would occur via steam methane reforming (SMR); however, in order to fit within carbon targets, **CCUS would be a necessity**, increasing costs (The Royal Society, 2018). Therefore the use of gas for H_2 will be dictated by its cost relative to other options such as electrolysis using excess renewable electricity generation. The Committee on Climate Change currently believes that SMR with CCUS is the cheapest viable H^2 production option and therefore includes 53-225 TWh of H_2 from this route in its net zero scenarios, compared to only 44 TWh of H_2 from electrolysis (Committee on Climate Change, 2019b). This agrees with other work also suggesting that SMR with CCUS is much cheaper – by approx. a factor of 4 – than electrolysis (Parkinson et al., 2019). In contrast, however, the Royal Society highlights the prediction that SMR-CCUS costs will be similar to other H_2 routes such as coal and biomass gasification and, in some cases, electrolysis (The Royal Society, 2018). This suggests a competitive H_2 production economy in which SMR-CCUS is one option among several. Nevertheless, **it is likely that the major use of natural gas in future will be H^2 production with carbon capture**.

The extent of this particular role is uncertain for three main reasons:

i. SMR with CCUS must be deployed at large scale by 2030 (Committee on Climate Change, 2019b) but CCUS is not yet commercially mature;
ii. the carbon footprint of H_2 produced via SMR with CCUS is ~5.6 kg CO_2e/kg H_2 compared to only 0.8-2.2 kg for electrolysis using renewables or nuclear (Parkinson et al., 2019), therefore tightening emissions limits or taxes may constrain its deployment; and
iii. SMR with CCUS could be outcompeted on both costs and emissions by developing technologies such as nuclear thermochemical electrolysis using either the S-I or Cu-Cl cycle, the latter of which might use waste heat from nuclear power generation, further reducing costs (Parkinson et al., 2019).

Another possible role for shale gas is high temperature industrial heat provision. This is due to the difficulty and relative expense of existing methods of meeting high temperatures without combustion. The iron and steel industry is one such example of heavy industry with high temperature heat requirements. However, it should be noted that this currently comprises less than 1% of the UK's gas demand (BEIS, 2019a).

3 Average carbon footprint of UK electricity in 2018 = 263 g CO_2e/kWh (BEIS, 2019a, Bruckner et al., 2014). With a COP of 2: 263 ÷ (2 kWh × 3.6 MJ) = 36.5 g CO_2e/MJ heat.

Aside from the energy sector, the use of shale gas as a feedstock for petrochemical and plastic production has been cited as potentially significant industrially (INEOS Shale, 2015). Currently the total non-energy use of natural gas in the UK comprises only 0.6% of demand (BEIS, 2019a), but the associated supply of ethane from shale could be a major feedstock. In the USA, for instance, shale ethane has been credited with reviving the plastics industry (American Chemistry Council, 2015). The impact this could have on the decarbonisation of the UK is not clear at present.

Finally, it should be noted that the viability of all the above roles for shale gas is still contentious in the academic community. For instance, one recent study on the more cautious side of the debate stated that *"Fossil fuels (including natural gas) have no substantial role in an EU 2°C energy system beyond 2035"* (Anderson and Broderick, 2017).

5 Summary and Conclusions

This review has outlined the decarbonisation context for the UK, the findings of life cycle assessment studies and future energy scenarios, and the extent to which shale gas might fit into the UK's future.

The UK is navigating a global context of ever-tightening greenhouse gas emission targets within which the pace of decarbonisation must inevitably be higher for advanced economies than for developing economies. **Legislation in the UK binds us to achieve 'net zero' emissions by 2050, requiring very rapid, completely unprecedented reduction in GHG emissions**, perhaps up to a rate of ~12% per year.

The use of life cycle assessment has been widespread in the energy sector for many years, and **assessments of shale gas have typically found carbon footprints of around 500 g CO_2e/kWh of electricity, or 67 g CO_2e/MJ of energy content**. This is approximately 10% lower than the carbon footprints of imported LNG (although LNG has variable and somewhat uncertain impacts). There are various areas of uncertainty within these assessments, such as an appropriate 'estimate ultimate recovery' (i.e. the lifetime gas output of a shale gas well) and the methane emissions associated with different specific operations on-site.

The UK's electricity sector must be close to zero-carbon by the 2030s and therefore, even with carbon capture and storage, gas is unlikely to play a major role. In the heat sector, the majority of the UK's heat is low-temperature, in which other **competing technologies such as heat pumps have a much lower carbon footprint than conventional or shale gas**. Legislation is in place and progressing to limit the use of gas for low-temperature heat in the coming decade.

It appears likely that **the major future role for shale gas will be in the production of H_2 via steam methane reformation with carbon capture and utilisation/storage**. This would be used primarily as a heating and transport fuel. Some scenarios include up to 225 TWh/yr by this route. However, other scenarios exist with minimal H_2 or with H_2 produced by other means.

Shale gas may also play a role in high-temperature heat for heavy industry, in which decarbonisation is harder to achieve. However, this currently comprises only a small percentage of UK heat demand and, again, will require carbon capture in the mid- and long-term future, further increasing costs.

Overall, based on the current state of scientific literature in this area and our decarbonisation requirements, one might conclude the following: **the role of gas without carbon capture is rapidly diminishing. If a future role exists for shale gas it is likely in hydrogen production with carbon capture. At most, this role will be smaller than the current role of natural gas.**

7 About the Author

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