UK Energy Research Centre

The future role of natural gas in the UK

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Research Councils UK Energy For a Low Carbon Future

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Executive Summary

The UK has statutory greenhouse gas emission reduction targets through to 2050, which mandates an 80% reduction in emissions by that date from the level in 1990. Meeting this target cost-effectively will require at least a similar reduction in carbon dioxide emissions from the UK energy system by that date.

Natural gas has significantly lower CO_2 emissions on combustion per unit of energy delivered than either coal or oil, but higher emissions than nuclear and most renewable energy sources. Questions therefore arise about the role of gas as the UK seeks to move cost-effectively towards a low-carbon energy system. How much gas use is compatible with meeting the UK's carbon emissions reductions targets? How is this affected by whether carbon capture and storage technology (CCS) is available? Can gas, by substituting for coal, act as a 'bridging fuel' to a low-carbon UK energy system and, if so, how much gas use does such a bridge entail, and over what period of time[1]? These are the questions which are addressed in this report.

The results of the research also give significant insights into the implications of the recent energy policy announcements by Amber Rudd MP, the UK's Secretary of State for Energy and Climate Change. These announcements include, most pertinently, the phase out by 2025 of power generation in the UK from coal, with the construction of new gas-fired power stations as their principal replacement and, in the November Comprehensive Spending Review, the decision to cancel the UK's £1bn CCS demonstration programme.

The substitution of coal by gas in the UK's energy system has been occurring since at least 1970. Initially the substitution was mainly for energy use in buildings and industry, with the major reductions in coal use occurring over 1970-1980. This continued later in power generation, with the so-called 'dash for gas' over 1990-2000. These substitutions meant that by 2014 the share of coal in UK primary energy consumption had fallen from 40% in 1970 to 16%, while gas use had increased from 5% to 47%.

Of the remaining coal use in 2014, nearly 80% was in the electricity sector. Replacing this immediately with 30 GW of CCGTs, operating at the 40% load factor that was the average for such power stations over 2010-2014 could reduce emissions by over 80 Mt CO_2-eq per year. This is a significant reduction, exceeding the emission reductions required under the 3rd carbon budget covering the period 2018 to 2022.

However, in reality the realised emissions savings would likely be significantly less. Not only would it take a considerable time to build so many new power stations, but also the use of coal in power stations is in any case projected to reduce in future years. Following the recent government announcement, coal generation is planned to cease entirely by 2025. After 2025, if the carbon targets are to be cost-effectively met, the use of gas in power stations would need to decline, especially if they were not fitted with CCS, further reducing the load factors at which the new CCGTs could operate. This would raise questions as to the economic viability of investing in these gas-fired stations, rather than low- or zero-carbon power generation, in the first place. These issues are further explored in the scenario analysis that forms the main content of this report.

Two models were used to generate these scenarios, which are designed to analyse a range of possible futures. Both are optimising energy system models, which minimise energy system costs, or maximise the social welfare that they deliver, under different scenario assumptions.

The first of these models developed by the Energy Technologies Institute (ETI), is called ESME.[2] This model was used to generate a large number of sensitivity scenarios with a wide variety of technological, resource, and price assumptions to explore the affects these key uncertainties have on the development of the future energy system. From these runs, carbon capture and storage (CCS) emerges as a critical technology if gas is to have a significant role, consistent with UK carbon

[1] Gas acting as a 'bridge' to a low-carbon future is used here to mean when gas consumption, in a scenario that is consistent with maximum 2°C temperature average global warming, increases either absolutely from 2010 or relative to another scenario that does not meet this temperature constraint.

[2] The ESME version used in this analysis is the same as that used in Pye et al. 2015. It is based on the ESME v3.2 release, but is quite distinctive in respect of the input assumptions. Therefore, any results presented should in no way be attributed to the ETI.

Natural gas has significantly lower emissions on combustion per unit of energy delivered than either coal or oil, but higher emissions than nuclear or most renewable energy sources

reduction targets, out to 2050. Indeed, without CCS, UK gas consumption should fall continuously through to 2050 to only about 12% of the 2010 level if the UK is to meet the 80% emissions reduction target.

The second model, called UKTM, is used to project the future of UK energy use under five discrete, but more precisely characterised, scenarios. Three of these scenarios do not meet some of the UK's emission reduction targets. Two of them comply with legislated carbon budgets and the 2050 target. Note that we have included the non-compliant scenarios so that a wider range of futures than usual can be explored, and to inform debate and decision making. However, this should not be interpreted as a desire to see any relaxation of the UK's statutory climate change targets.

In the two UKTM scenarios that meet the 80% carbon emissions reduction target for 2050, the availability of CCS, as in the ESME runs, makes a huge difference to 2050 gas use. Figure E1 summarises gas consumption over time for these two scenarios: **Maintain** and **Maintain (tech fail)**.

The differences up to 2030 between **Maintain** and **Maintain (tech fail)**, the latter of which assumes that CCS cannot be deployed, are not so great. Reductions in power generation emissions deliver most of the decarbonisation necessary by this date through reduced gas use. But by 2050, gas with CCS in **Maintain** has created a whole new sector through the production of hydrogen. This is used both in transport and industry in roughly equal proportions. The availability of this new low-carbon energy vector aiding the decarbonisation of these sectors permits the use of gas in buildings to be much higher in **Maintain** than would otherwise be possible. A small amount of gas use also remains in the electricity sector in both scenarios, to balance intermittent renewables, and in industry. The small amount of gas use in transport in 2030 in both scenarios is compressed natural gas (CNG) used in heavy goods vehicles, but the emissions constraint means that this has disappeared by 2050.

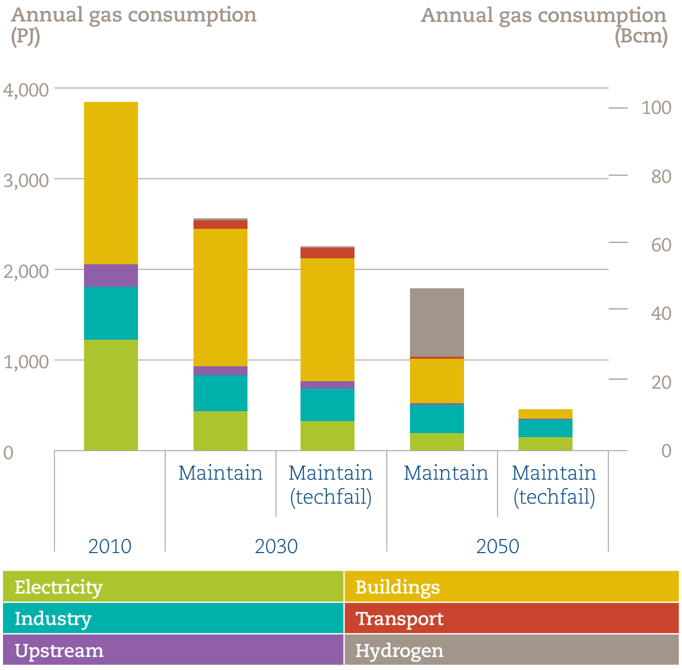
These scenarios permit a fairly clear conclusion to emerge about the possible role of gas in the UK as a 'bridging fuel' to a low-carbon UK energy system. Figure E2 shows the trajectory of gas consumption in the two UKTM scenarios that meet the 2050 carbon target, compared with that of the **Abandon** scenario, which only meets the 3rd carbon budget, but does not meet the 2050 target. It can be seen that gas consumption in the two low-carbon scenarios briefly rise above that in **Abandon**, but after 2020 it soon falls to below it and continues to decline through to 2050, while gas use in **Abandon** remains broadly unchanged.

These scenarios permit some strong conclusions to be drawn about future UK gas use, in the context of meeting UK carbon emission reduction targets in 2050.

The first conclusion is that gas is unlikely to act as a cost-effective 'bridge' to a decarbonised UK energy system. In this report, we have used the term 'bridge' to describe scenarios in which gas demand rises in future from current levels before declining; or in which there are emissions reduction scenarios that have higher gas demand than scenarios that do not include emisisons reduction targets. Our analysis shows that gas could only act as a bridge from 2015-20. We therefore conclude that gas is more likely to provide a short-term stop-gap until low- or zero-carbon energy sources can come on stream.

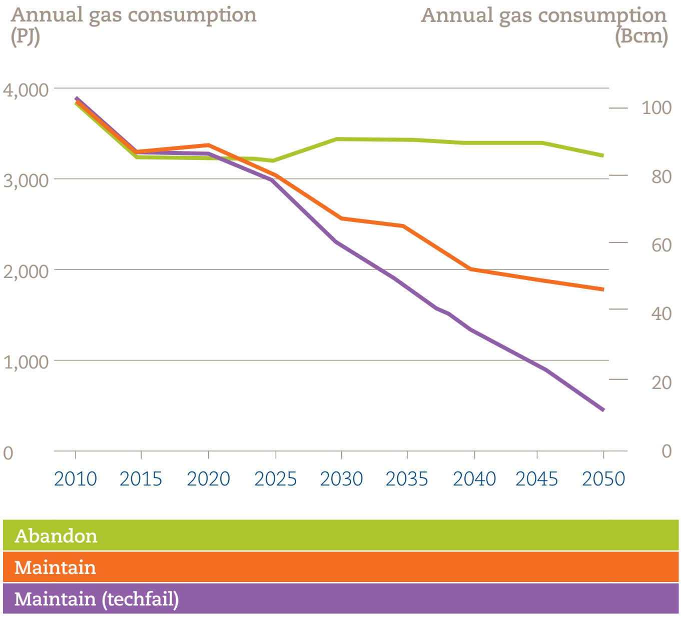
The second conclusion is that, without CCS, the scope for UK gas use in 2050 is little more than 10% of its 2010 level. The recent decision of the UK Government not to support CCS demonstration is therefore at odds with its seeming perception of a long-term future for UK gas consumption in a context of meeting the UK's carbon targets, unless it envisages that commercial-scale CCS will be developed and demonstrated elsewhere, and the technology subsequently imported into the UK.

Figure E1: Sector gas use in UKTM scenarios that meet the UK's 2050 carbon targets



Source: (Jones 2012a)[16]

Figure E2: Gas consumption over time in **Abandon, Maintain**, and **Maintain (techfail)**



The third conclusion is that, with or without CCS, there may be limited cost-effective scope for gas use in power generation beyond 2030. This is the case even though CCS is clearly beneficial to helping the UK meet its emissions reductions. This means that gas-fired power stations built between now and then will need to operate on relatively low load factors, which is something that investors will doubtless take into account in their decision whether to invest in these power stations. Such considerations may be behind Amber Rudd's acknowledgement in her recent announcement that new gas-fired power stations will need subsidy in the form of assurance of future returns if they are to be built.

The fourth conclusion is that, with or without CCS, meeting the 2050 target will constrain the role for natural gas in the UK's energy system in the 2020s and beyond. Both the ESME modelling and the UKTM scenarios make this clear. The nature of that role is dependent on other developments in the wider energy system—such as new nuclear, the rate of energy efficiency improvement and the scale of renewable energy—and the availability of key technologies. The ESME results show the significance of CCS to keeping gas in power generation and certain sectors of industry. Without CCS gas must be steadily phased out over the next 35 years and almost entirely removed by 2050. This represents a major challenge in relation to the decarbonisation of domestic heat and potentially undermines the economic logic of investing in new CCGT gas power generation capacity.

The take-home message from this report is clear. The UK debate should not be reduced to a choice between a future with gas and a future without it. However, if all coal-fired power generation is to be removed by 2025, and the Government is no longer willing to support the development of CCS, policy makers must think very carefully about how best to replace that capacity. A 'second dash for gas' may provide some short term gains in reducing emissions. However, this may not be the most cost-effective way to reduce emissions and, in the absence of CCS technologies, it may well compromise the UK's decarbonisation ambitions.

1. Introduction and background

Natural gas has the lowest combustion carbon intensity of the three major fossil fuels

1. Introduction and background

Natural gas has the lowest combustion carbon intensity of the three major fossil fuels (see e.g. IPCC (2006)). However, it has been shown that increases in the consumption of natural gas are not sufficient for reducing global greenhouse gas emissions since this would potentially substitute for both higher-carbon fossil fuels, e.g. coal or oil, as well as for lower-carbon or zero-carbon energy sources, such as renewables (McJeon et al. 2014). McGlade et al. (2014) and McGlade & Ekins (2015) examined possible futures for fossil fuels, with a particular focus on the 'bridging' role that natural gas may be able to play during a transition to a global low-carbon energy system. This research found that there is a good potential for gas to act as a transition fuel to a low-carbon future up to 2035 on a global level, but only under certain conditions.

This is consistent with the views of the Intergovernmental Panel on Climate Change (IPCC), which indicated that in a global context '***GHG emissions from energy supply can be reduced significantly by replacing current world average coal-fired power plants with modern, highly efficient natural gas combined-cycle power plants or combined heat and power plants***' (IPCC 2014, p.22).

However, one of the key caveats to the positive conclusion that natural gas can play a 'bridging' role globally is that its potential varies significantly between different regions. Therefore while some national-level studies have demonstrated that increases in natural gas consumption, in combination with certain emissions-reduction policies, can help reduce overall greenhouse gas emissions in the United States (Moniz et al. 2010), it does not follow that this is the case in all countries and regions around the world. It is also noteworthy that the International Energy Agency (IEA)'s (2011) 'Golden Age of Gas' scenario that explored a future with more natural gas in the global energy system resulted in 3.7°C of global warming, well above the internationally-agreed threshold of 2°C .

This report explores the potential role of natural gas in the UK through to 2050, in the context of its statutory greenhouse gas emissions targets. The two key questions that it seeks to answer are:

1. What has been the historical role of coal-to-gas substitution in decarbonising the UK energy system and what potential remains?
2. How might the role of gas in the energy system change in the future and to what extent can gas act as a bridging fuel towards a low-carbon energy system in the UK?

While the answers to these questions will show whether or not natural gas can confer benefits from an emissions reduction perspective, climate change policies are only one dynamic affecting future levels of gas consumption. Bradshaw et al. (2014) highlighted the myriad of technological, economic, and policy factors that will affect gas consumption in the UK and put these into a global context. The range of uncertainties around these factors means that how large natural gas consumption might be and what role it might play in the future, in the UK and elsewhere, depends on the assumptions about these factors and therefore remains an open question.

This is important given the debate surrounding the role of natural gas in the future of the UK energy system, particularly the high levels of controversy around the pros and cons of exploiting potential domestic shale gas resources (Bradshaw 2016). In 2014 natural gas accounted for 34.1 % of total UK primary energy consumption; of that 32 % was used in the generation of electricity and heat by power stations; 36 % by households, mainly in heating buildings, and the remainder by industry and other users. In the same year, UK production—almost entirely from the North Sea—accounted for 48 % of UK gas consumption; while Norwegian imports provided 30 %; LNG shipped from Qatar 13 % of consumption; and the remaining 9% came from continental Europe via the two interconnectors (DECC 2015a)

A key point that is often missing in the shale debate is how gas consumption could change in future

The UK's domestic gas production peaked in 2000 and it became a net importer in 2004. A decade later the UK imports about half the gas it needs. This rising import dependence has been enabled by the expansion of pipeline and LNG import infrastructures and by a competitive domestic gas market that provides a significant amount of resilience (DECC/Ofgem 2015). Although UK gas prices have been affected by international factors for many years, UK consumers are now more exposed to developments in the European gas market and the global LNG market (Bradshaw at al. 2014). As gas production in the North Sea will continue to decline, the rate at which import dependency might increase will be determined by the absolute domestic demand for gas and any future potential production from both conventional and unconventional (including shale) gas.

This report is not specifically about shale gas – it is about the wider UK gas market. However, a key point that is often missing in the shale debate is how gas consumption could change in future, and to what extent gas use can be compatible with UK climate change targets. In this report we therefore explore what overall role natural gas could play in a future transition to a low-carbon UK energy system.[3] This is a separate issue from the potential for UK production of shale gas, which may or may not be used in the UK. Separating the issues, which are frequently conflated, helps clarify the points under discussion.

It should be noted that the scenario analysis presented in this report was completed before Amber Rudd MP, the Secretary of State for Energy and Climate Change, gave her 18 November 2015 speech: 'A New Direction for UK Energy Policy'. Consequently, our scenarios are not explicitly aligned with the UK Government's new policy direction, but they do shed light on the consequences of having no coal-fired power generation after 2025 and potentially a greater role for gas-fired power generation. Similarly, the implications of the Government's subsequent decision in the Comprehensive Spending Review to cancel the £1 billion competition for the development of carbon capture and storage (CCS) technology are also made clear through our various scenarios.

In this report, we use the energy system models UKTM (Daly et al. 2015) and ESME (Heaton 2014) to examine changes in the role of gas in the UK under a range of future energy scenarios. We use two alternative models here for a variety of reasons. First, the set-up and assumptions within these models vary and so we avoid drawing firm conclusions based on only a single model. Second, even while exploring similar issues, the two models are better suited to constructing different types of scenarios. Nevertheless, these models have many features in common, as discussed in the following section). Therefore, to supplement further our analysis and to provide further context for our results, we also examine long-term projections of UK gas consumption by National Grid.

[3] Note that the life cycle emissions of gas production from different sources is beyond the scope of this report. For an overview of the evidence base on these emissions, including significant remaining uncertainties, see MacKay and Stone (2013) and Balcombe et al (2015). Decarbonising gas consumption, at least partially, by replacing some proportion of natural gas with biogas (e.g. from anaerobic digestion) is also beyond the scope of the report, but offers some potential of continuing to use existing gas infrastructure with lower carbon emissions.

2. Modelling approach and scenarios constructed

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This section gives an overview of the two energy system models that have been used for the analysis – UKTM and ESME – and the scenarios that will be implemented with each.

As noted, these models have some features in common. They tend to optimise energy system developments (minimising energy system cost or maximising a measure of social welfare) by assuming rational decision making by a single decision maker who has perfect information about the future. Such assumptions are not realistic, of course, but such models nevertheless provide important insights about how energy systems could change in response to drivers such as fuel prices and emissions limits – and some of the trade-offs and choices that could be important.

2.1 Overview of ETI's ESME[4]

ESME (Energy Systems Modelling Environment), developed by the Energy Technologies Institute (ETI), is a fully integrated energy systems model, used to determine the role of different low carbon technologies required to achieve the UK's mitigation targets. The model has been used in this capacity by the UK Department for Energy and Climate Change (DECC) and the UK Committee on Climate Change (CCC) (CCC 2013; CCC 2010; DECC 2011). Built in the AIMMS (Advanced Interactive Multidimensional Modelling System) environment, it uses linear programming to assess cost-optimal technology portfolios. The uncertainty around cost and performance of different technologies and resource prices is captured via a probabilistic approach, using Monte Carlo sampling techniques.

The representation of energy demand sectors is typical of other energy systems models. The model endogenously determines how to meet these demands in the cost-optimal manner, through investment in end use technologies (including efficiency measures), production and supply of different energy forms, and via reductions in the demand for energy services (as described in the next section in relation to the UKTM model). In the household sector, a rich characterisation of low carbon technologies is provided, particularly for heat pumps, district heating (including infrastructure) and building fabric retrofit. The transport sector also incorporates the key low carbon technologies, and the different infrastructures required to deliver alternative fuels e.g. electricity charging infrastructure and hydrogen networks. The industry sector is characterised more simply, focusing on efficiency gains, fuel switching measures and carbon capture and storage (CCS). The key low carbon technologies are represented in the transformation sectors (power generation, hydrogen production, biofuel production) and associated infrastructures (to enable inter-node transmission). Primary resource supply is characterised by commodity price and resource availability, with no distinction between imports and domestic indigenous production (except for biomass). Further information is provided in Heaton (2014).

2.2 Overview of UKTM

The quantitative energy system analysis is conducted with the new national UK TIMES energy system model (UKTM). UKTM has been developed at the UCL Energy Institute over the last two years as a successor to the UK MARKAL model (Kannan et al. 2007). It is based on the model generator TIMES (The Integrated MARKAL-EFOM System), which is developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) (Loulou & Labriet 2007).

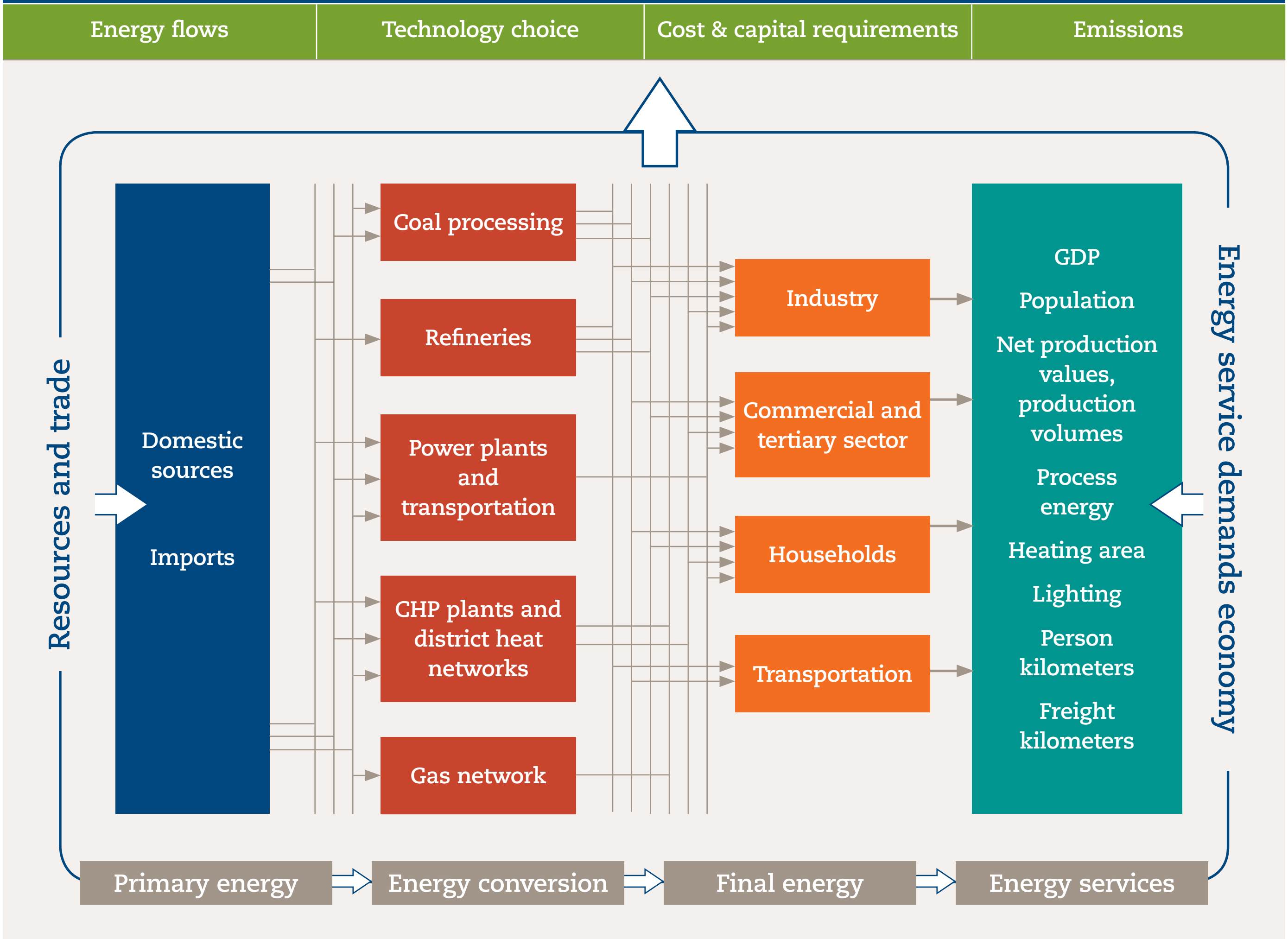
UK MARKAL was largely developed by UCL within UKERC, and was used as a major underpinning analytical framework for UK energy policy making and legislation from 2003 to 2013 (Ekins et al. 2011; DTI 2007; CCC 2008; DECC 2011), and UKTM continues to perform this role as the central long-term energy system pathway model used for policy analysis at the Department of Energy and Climate Change (DECC) and the Committee on Climate Change (CCC). It has been used for their analysis of the 5th Carbon Budget, which sets the limit on GHG emissions in the UK for the period from 2028 to 2032 and informed the UK's negotiating position at the United Nations Climate Change Conference (COP 21) in December 2015. With the aim to increase the transparency in energy systems modelling and to establish an active user group – including key decision makers – an open source version of UKTM is being prepared that will be updated on a regular basis.

UKTM is a technology-oriented, dynamic, linear programming optimisation model representing the entire UK energy system (as one region) from imports and domestic production of fuel resources, through fuel processing and supply, explicit representation of infrastructures, conversion to secondary energy carriers (including electricity, heat and hydrogen), end use technologies and energy service demands. Like other models of this type, as noted above, it minimizes the total welfare costs (under perfect foresight) to meet the exogenously given sectoral energy demands under a range of input assumptions and additional constraints and thereby delivers an economy-wide solution of cost-optimal energy market development.

The model is divided into three supply side sectors (resources & trade, processing & infrastructure and electricity generation) and five demand sectors (residential, services, industry, transport and agriculture).

[4] The ESME version used in this analysis is the same as that used in Pye et al. 2015. It is based on the ESME v3.2 release, but is quite distinctive in respect of the input assumptions. Therefore, any results presented in this report should in no way be attributed to the Energy Technologies Institute.

Figure 1: Schematics of features of UKTM



Source: Adapted from Remme et al. (2002)

All sectors are calibrated to the base year 2010, for which the existing stock of energy technologies and their characteristics are taken into account. A large variety of future supply and demand technologies are represented by techno-economic parameters such as the capacity factor, energy efficiency, lifetime, capital costs, O&M costs etc. Moreover, assumptions are laid down concerning energy prices, resource availability and the potentials of renewable energy sources, etc. UKTM has a time resolution of 16 time-slices (four seasons and four intra-day times-slices). In addition to all energy flows, UKTM tracks CO_2, CH4, N2O and HFC emissions. The model structure is illustrated in Figure 1. For more information on UKTM see Daly et al. (2015).

2.3 ESME scenarios

As discussed above, ESME is well suited to exploring the effects of uncertainty on future energy and emissions pathways. We therefore use this strength here to explore the effects of uncertainty in technology investment costs in the power and transport sectors, fuel costs and resource potential e.g. biomass imports, on future levels of gas consumption in the UK under different emissions assumptions. In the context of these uncertainties, we explore three specific scenarios that have been shown previously to have a large effect on the levels of gas consumed. These three scenarios are:

(i) A reference case which is required to meet the 4th carbon budget (a 50% reduction on 1990 emission levels by 2025) but with no other explicit requirements to reduce greenhouse gas (GHG) or CO_2 emissions thereafter;

(ii) An 80% GHG emissions reduction by 2050 case in which CCS is permitted; and

(iii) An 80% GHG emissions reduction by 2050 case in which CCS is not permitted.

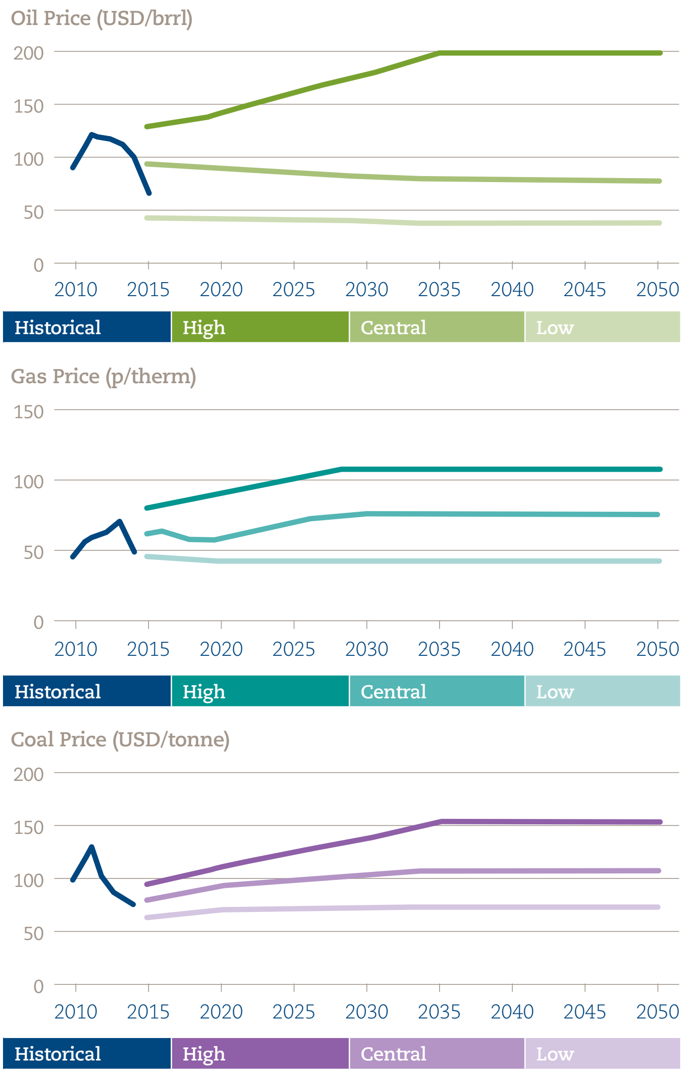
A detailed description of the uncertainties explored is provided in Pye et al. (2015) and these are summarised in Table 1 below. A Monte-Carlo simulation process is used to explore these uncertainties with 250 runs implemented for each of the above three scenarios. As with all scenarios in this work, we analyse the effects that these scenarios and sensitivities have on UK gas consumption.

Since one of the uncertainties explored using ESME concerns resource prices, it is worth commenting briefly here on the fossil fuel price assumptions. As of 1st February 2016, Brent oil was priced at around $35/bbl, spot National Balancing Point prices for gas were at around 30p/therm, while the average price of coal purchased by major power producers in the third quarter of 2015 was £47/tonne (DECC 2015b). All three of these prices were below the 'low' projections produced by DECC (2014) for fossil fuels prices in 2015 and 2016, with oil more than 60% lower. This clearly demonstrates the difficultly in providing fossil fuel price projections that can be considered reliable.

It is for this reason that we explore price uncertainty using ESME, and indeed in some of the UKTM scenarios below. It should be remembered, however, that both of these models look at long-term dynamics, and cannot be relied upon (or expected) accurately to project or reproduce short-term behaviour. In other words, where the oil or gas prices will be in six months or the next year or two is not a driving factor behind the set-up of the models.

Future gas and coal prices in the central, low and high cases in both UKTM and ESME continue to rely respectively upon the central, low and high DECC projections from 2014.[5] Nevertheless, given the dramatic change in oil prices since the end of 2014, it no longer seems reasonable to continue using the central DECC oil price projection. We therefore use the low DECC price projection for our 'central' estimate of oil prices and generate our own 'low' oil price projection based on prices that are always 50% of this. However, given the possibility that current oil prices will not remain as low as they are at present, and to take into account the range of possible future oil prices, we continue to use DECC's high estimates from 2014 for our 'high' oil price projection. Figure 2 summaries the price projections for oil, gas and coal used in both ESME and UKTM.

Figure 2: Fossil fuel price projections used in ESME and UKTM



Source: DECC (2014) and authors calculations

Table 1: Areas of uncertainty explored in ESME runs

Parameter	Sector	Approximate range of uncertainty
Investment costs	Power generation	Increases with novelty of technology from ±20% for mature technologies to ±70% central estimate for novel technologies
	Road transport	Increases with novelty of technology from ±10% for mature technologies to between +60% and -20% central estimate for novel technologies
	Heat pumps & district heating	±30% central estimate
Annual build rates	Power generation	± 50% central estimate
Resources	Biomass availability	+150% & -50% central estimate
	Prices	Around ±40% central estimate for gas and coal Around +150% and -50% central estimate for oil

[5] The Department of Energy and Climate Change (DECC 2015c) published revised fossil fuel price assumptions after this research was completed. Generally speaking, these have lower projections than the 2014 edition out to around 2025. However, the longer term projections, which have more influence on our modelling efforts, remain similar.

2.4 UKTM Scenarios

UKTM has a more detailed representation of the UK energy sector than ESME. It is therefore more complex, and may represent certain features of the energy system better, but there is a consequent trade-off with the time to run a specific scenario. As a result, we use it here to explore five better-defined but discrete scenarios with the following characteristics.

The first, called '**Abandon**' assumes that climate change policy is downgraded in importance during the late 2010s. The Climate Change Act is repealed in 2021, partly due to political opposition to the short-term costs of decarbonisation at a time of continued austerity, and partly due to a failure by the international community to implement the ambitious deal agreed in Paris in 2015. This means that further limits on emissions beyond the 3rd carbon budget (2018-22) are not implemented. The UK maintains its commitment to international trade and integration with international energy markets. However, because of a relative lack of emphasis internationally on moving away from fossil fuels, and consequently higher overall demand, the price of fossil fuels is relatively high in this scenario. Despite the repeal of the Climate Change Act, because of a desire to 'sweat' current assets and to ensure a continued commitment to EU Directives, the existing pledge that no new unabated coal power plants are to be constructed remains.

The second, **Insular**, scenario also assumes that climate change policy is downgraded in importance during the late 2010s. The Climate Change Act is repealed in 2021, for similar reasons to **Abandon**, which again means that further limits on emissions beyond the 3rd carbon budget are not implemented. As a reaction to economic problems at home and the perceived failure of international markets and institutions, UK citizens vote to leave the EU. It also shifts towards a more inward looking energy policy with, for example, much less electricity connection to the European continent. Strict limits are placed on imports in favour of domestic fossil fuel (including new coal) and renewable resources, and prices of fossil fuels are relatively high as a result.

The **Affordable** scenario continues with commitment to climate change targets well into the 2020s, but with an impression that the world is not acting sufficiently quickly to reduce emissions, this commitment starts to falter. This results in a lack of agreement on the 5th carbon budget (2028-32) because of the perceived high costs of meeting progressively challenging targets and so only the 4th carbon budget (2023-27) is met. The UK shifts away from any ambition to take a leadership position on climate change, and progressively argues for the EU to play a following role in international negotiations. Policies to support the deployment of renewables are progressively scaled back as is policy support for nuclear and CCS.

In the **Maintain** scenario, the UK continues its commitment to climate change targets (i.e. 80% GHG emissions reduction by 2050). The 5th carbon budget is agreed, broadly in line with Committee on Climate Change advice. Part of the reason for this is a relatively strong climate agreement in Paris and significant progress by many countries towards meeting their commitments. This drives down the costs of many low carbon technologies and energy efficiency measures and starts to remove trade barriers. This includes CCS technologies which are successfully commercialised and 'rolled out' alongside other low carbon technologies. Since the world shifts away from carbon-intensive fuels, particularly coal, fossil fuel prices remain relatively low.

The **Maintain (tech fail)** scenario is similar to **Maintain**, but there is a failure of efforts to commercialise CCS technologies. More emphasis is therefore placed on other forms of mitigation to meet UK targets such as renewables, nuclear power and energy efficiency.

Some of the key assumptions that vary across each of the above scenarios are set out in Table 2. The scenarios with 2050 emissions reduction targets are also required to keep within a cumulative level of emissions between 2028 (the end of the 4th carbon budget period) and 2050. This ensures that there is a steady progression towards the 2050 target and is used as a proxy for future carbon budgets to be set by the Committee on Climate Change. The cumulative constraint is constructed on the basis of a linear decrease from the maximum emissions level in 2028 to the level required in 2050. For example, **Maintain** has maximum emissions in 2028 of 430 Mt CO_2-eq and 160 Mt CO_2-eq in 2050. A linear decline between these dates yields total emissions of 6750 Mt CO_2-eq, which is therefore imposed as a cumulative limit on emissions between these dates in this scenario.

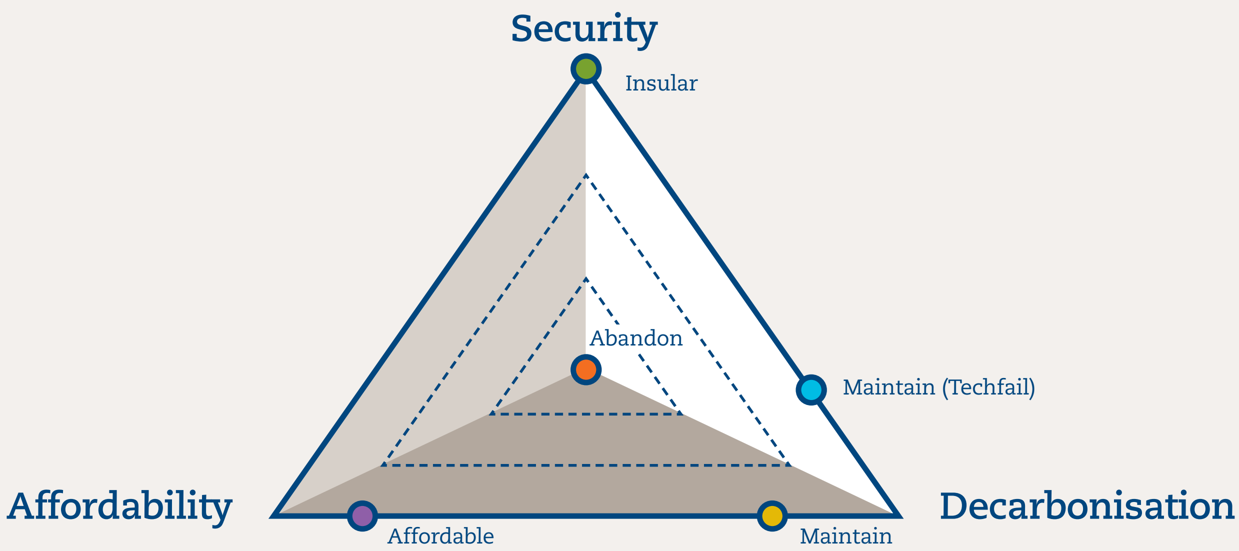
The above scenarios can be visualised with respect to the 'Energy Trilemma' (see, for example, World Energy Council 2015) of the interplay and tensions between the goals of emissions reduction (decarbonisation), 'keeping the lights on' (energy security), and the affordability of energy for consumers (called 'equity' in the WEC version of the trilemma). It is noteworthy that the UK lost its AAA rating in the 2015 WEC benchmarking exercise because the rising cost of electricity at the time reduced its 'equity' score to a B.

Table 2: Core assumptions varied across the UKTM scenarios

Scenario Name	Emissions reduction	Technology	Fossil Fuel Prices	Import dependency
Abandon	35% reduction by 2020	No new coal Nuclear delay	High	Outcome of the model
Insular	35% reduction by 2020	Max interconnector 4 GW	High	Max 30% primary energy in 2020, falling to 5% by 2030
Affordable	50% reduction by 2025 60% reduction by 2050	Slow renewables deployment Delay in new nuclear Delay in CCS	Low	Outcome of the model
Maintain	80% reduction by 2050	No new coal	Central	Outcome of the model
Maintain (Tech failure)	80% reduction by 2050	No new coal No CCS	Central	Outcome of the model

Figure 3 shows a diagram of the Energy Trilemma, positioning in which represents policy priorities within each scenario[6], rather than the assumed result of any scenario1. In **Abandon**, for example, the repeal of the Climate Change Act, a failure to support or allow the cheapest forms electricity production, no efforts to mitigate emissions globally and an assumption that energy prices will be high mean that the scenario would potentially fail to fully achieve any of the trilemma objectives. Therefore, it is equidistant from all the corners of the diagram. **Insular**, **Affordable** and **Maintain** concentrate primarily (though not exclusively) on one of the main goals, and so are located towards the corners of the diagram. However, there is, for example, a slightly greater emphasis on emissions mitigation in **Affordable** than in **Insular** (since the former is required to fulfil the 4th carbon budget while the latter is not), meaning that it is positioned slightly closer to the 'decarbonisation' corner. **Maintain (tech fail)** is placed slightly along the 'security' axis but also further from the 'affordability' corner than **Maintain**. **Maintain (tech fail)** excludes CCS, but still needs to meet decarbonisation objectives. It is therefore likely that there will be more emphasis on domestic renewable and efficiency measures rather than importing fossil fuels for use in centralised power plants.

Figure 3: UKTM scenarios located within the energy trilemma



[6] A comprehensive analysis of the implications of these scenarios for energy security and affordability is beyond the scope of this report. A separate UKERC project is underway that is analysing the security implications of these scenarios.

3. Coal-to-gas substitution in the past and future

3

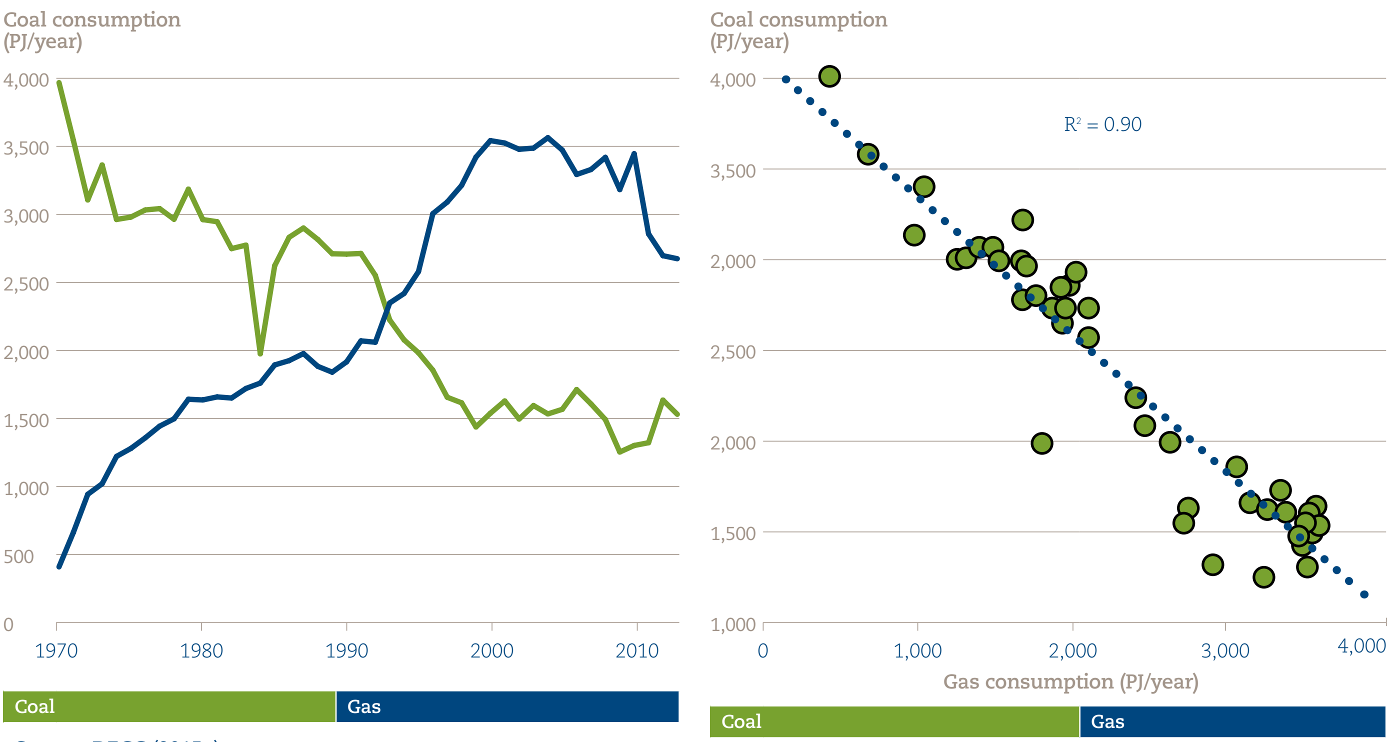
3. Coal-to-gas substitution in the past and future

This section turns to the question of what has been the historical role of coal-to-gas substitution in decarbonising the UK energy system and what potential remains. Previous analysis by McJeon et al. 2014), McGlade et al. (2014) and McGlade and Ekins (2015) has suggested that one of the principal mechanisms by which natural gas can assist with GHG emissions reduction is through coal-to-gas substitution. Before looking at possible future scenarios of gas consumption in the next section of this paper, it is therefore worth reflecting on the historic relationship between gas and coal consumption in the UK and what the remaining potential is for coal-to-gas switching to bring about greenhouse gas emissions reduction.

UK coal and gas consumption from 1970, broadly the beginning of substantive production of oil and gas from the North Sea, is presented in Figure 4. Coal consumption is now more than 60% lower than it was at the beginning of the 1970s, while gas consumption has risen by around six times over the same period. In 1970, coal accounted for over 40% of total primary energy supply with gas less than 5% (oil was 50%, and nuclear and renewable sources also less than 5%). The changes seen in Figure 4 meant that by 2012, the share of coal had halved to 20% and the share of gas had risen to 35% (oil had also shrunk to 30%, and nuclear and renewable sources grown to 15%).

As shown in the right hand side of Figure 4, there is a clear relationship between these two fuels, which exhibits a relatively strong inverse correlation. Clearly the rise of gas is not the only causative reason for the drop in coal. But it is nevertheless interesting that over the past 45 years, rises in UK gas have on average been matched by reductions in coal consumption of around three quarters the magnitude. Figure 3 also shows that the stagnation of the growth in gas from around the year 2000 was also similarly matched by a reduction in the rate of decline of coal.

Figure 4: Changes and relationship in UK coal and gas consumption



Source: DECC (2015a)

Between 1970 and 1980 natural gas replaced the majority of coal in the residential and services sectors

Figure 5 examines the sectoral breakdown of these changes in consumption. It can be seen that between 1970 and 1980 natural gas replaced the majority of coal in the residential and services sectors (panel (a)). Coal fell by over 70% with gas use tripling and overall emissions dropping by 15%. This drop in emissions occurred despite a net rise in total fuel consumption, indicating that it was almost entirely a result of coal-to-gas switching. It is important to note that there was around 300 PJ of town gas[7] consumed in the residential sector in 1970. While entirely new high-pressure transmission and distribution pipeline networks needed to be constructed to transport natural gas, low-pressure pipes that ran into people's houses, which had been used to transport town gas, could be much more easily switched to natural gas (Dodds & Demoullin 2013). This greatly aided the rapid rise in natural gas and the switch away from coal. After 1980, gas use continued to rise although this resulted from growing overall demand rather than any further significant coal-to-gas switching (although this did still occur to some degree). Indeed between 1990 and 2000, the continued expansion in the use of gas meant that overall CO_2 emissions rose in the residential and services sectors, reversing the trend seen in the past two decades.

Coal consumption dropped by over 60% in the industrial sector between 1970 and 1980 while gas use again more than tripled (panel (b)). Sectoral emissions fell by a third although this was also caused by a drop in overall energy consumption in the sector. Between 1980 and 1990, there was very little change in coal or gas use with the main change a halving in the use of oil. Gas use did then expand slightly over the next decade with a drop in both coal and oil consumption, but it can be seen that this had little overall effect on emissions, which fell by less than 5%.

A different picture emerges in the electricity sector (panel (c)), in which gas use was only permitted from 1989. Together with privatisation and liberalisation of the electricity and gas industries and the availability of efficient, low-cost combined cycle gas turbine technologies, this resulted in the 1990s 'dash-for-gas'. Almost 20 GW of new gas capacity was built in the decade. This was accompanied by a 40% drop in coal use, and a 15% fall in sectoral CO_2 emissions. While there was an additional 15% increase in gas between 2000 and 2010 and a 10% drop in coal, this change was much more muted than had been witnessed in the previous decade, and had only a minor impact on emissions. As with the industrial and buildings sectors, it is therefore clear that coal-to-gas switching can occur rapidly and result in a real drop in CO_2 emissions.

Panel (d) of Figure 5 demonstrates that the sectoral changes described above have resulted in a significant change in fuel consumption in the UK since the 1970s. Overall emissions dropped by over 10% between 1970 and 1980, largely thanks to coal-to-gas substitution in the industrial and buildings sectors, and then by a further 7% between 1990 and 2000 because of shifts in the electricity sector. The 15% fall in emissions subsequent to 2000 has largely been caused by other factors, however.

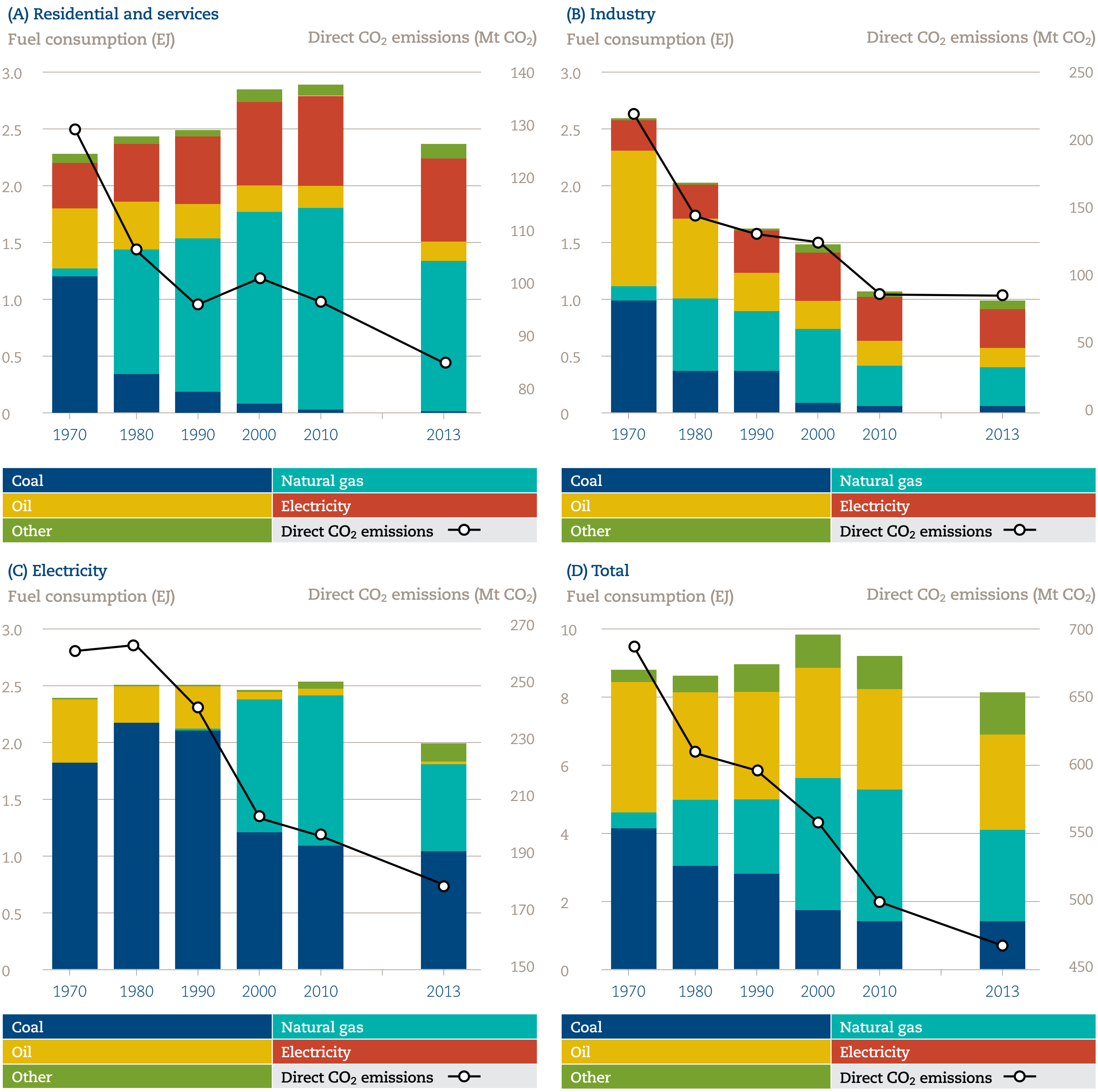
This significant substitution away from coal in the UK is, however, a relatively rare occurrence. In all countries outside of Europe, and indeed for a third of countries in Europe, the five-year average coal consumption around 2010 was greater, and generally much greater, than that around 1970 (Figure 6). It is evident that while the UK has been transitioning away from coal, many other countries around the world have been increasing their coal consumption.

In summary, despite the significant transition away from coal, it continues to represent a significant share of primary energy supply in the UK (16.4% of primary energy consumption in 2014), but the potential scope for coal-to-gas switching is now much more limited than was the case in the past. This is because the UK has already undertaken substantial coal-to-gas substitution and its GHG emissions are consequently lower. Indeed, the displacement of coal by gas accounts for the majority of the 20% drop in emissions witnessed between 1970 and 2000. The UK is therefore in a very different situation to most other countries in that it has already removed coal from nearly all but the electricity sector.

[7] Town gas, manufactured from coal, was a mixture of hydrogen, carbon monoxide, methane and other gases. It is not included in the natural gas numbers in Figure 5.

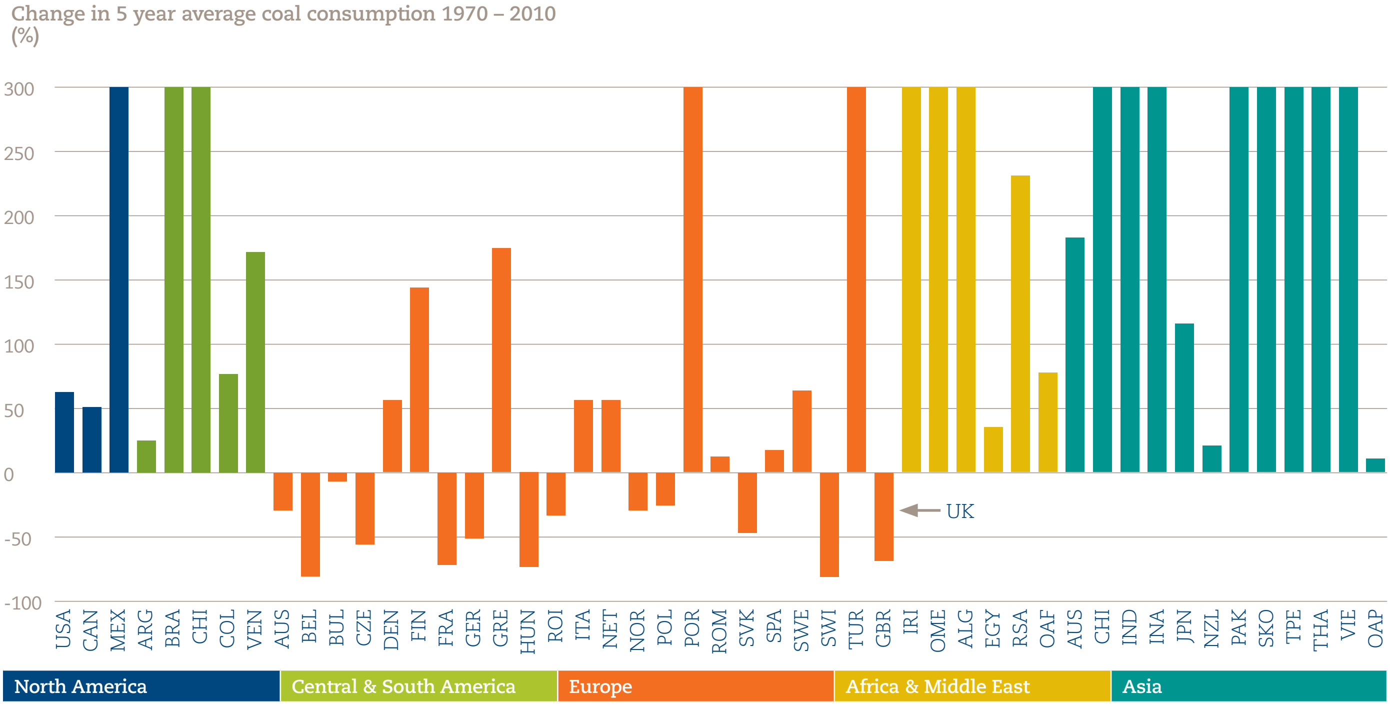
It is evident that while the UK has been transitioning away from coal, many other countries around the world have been increasing their coal consumption

Figure 5: Sectoral fuel consumption and CO_2 emissions since 1970



Source: DECC (2015a)

Figure 6: Changes in coal consumption in world regions between 2010 and 1970



Note: Countries with no consumption in 1970 have been excluded and increases in 18 countries are greater than 300%.
Source: BP (2015)

Therefore the UK has already travelled some way across the 'bridge' that gas can offer to a lower-carbon energy system.

With respect to the coal that remains in the UK's energy system, it has been argued that a 'no brainer' way to reduce greenhouse gas emissions is to replace it with gas-fired generation (Helm 2014, 2015).

It is worth examining the figures behind this to explore this possibility, as, given the above, it seems clear that as long as coal remains in the energy system, greenhouse gas emissions reductions can be brought about through coal-to-gas switching. In 2014 the UK consumed 1,320 PJ of coal, 79% of which was in the electricity sector, 13% was for the manufacture of coke or mineral products, and the remaining 8% was used for heat. This resulted in 123 Mt CO_2-eq greenhouse gas emissions[8] and a total of 363 PJ of electricity was generated from coal power plants.

We assume that the energy from coal used for heat (105 PJ) can only be substituted by energy from gas on a one-to-one basis. However, for electricity the IEA (2014) indicates that modern combined cycle gas turbines (CCGT) can have thermal efficiencies of 60%, significantly higher than the efficiency of existing coal power plants (35% using the IEA figures for 2014). The coal used for power generation (1045 PJ) could therefore be replaced by 605 PJ of natural gas, to produce the same amount of electricity. This would require the construction or return to service of around 13 GW CCGT capacity, if the capacity is available to be used 90% of the time. However, nearly 30 GW would be required if these CCGTs were only to have the average load factor of such plants in the UK between 2010 and 2014, which was 40%. In the short-run, the phase out of coal-fired power generation may lead to an increase in load factors, but in the medium- to long term (2025-2050) the load factors will likely fall again.

On these assumptions, a total of 710 PJ of natural gas would need to be consumed to save the 123 Mt CO_2-eq emissions associated with coal. This would result in around 40 Mt CO_2-eq GHG emissions, meaning that the coal-to-gas switching provides an annual saving of 83 Mt CO_2-eq. If additional CCGT plants could be brought online immediately, this would reduce emissions to 485 Mt CO_2-eq, which represents around a 15% saving on 2014 GHG levels (assuming that all else stays constant). This would therefore exceed the emission reductions required under the 3rd carbon budget. This budget requires average annual emissions between 2018 and 2022 to be below 510 Mt CO_2-eq.

While coal-to-gas substitution could therefore make a significant contribution to legislated near-term emission reduction goals, there are three key caveats to this conclusion. First, it is important to ask whether this is a cost-effective way of reducing the UK's greenhouse

[8] It would appear reasonable to assume that gas can only replace the coal used for electricity and heat. However, the emissions attributed to the consumption of coal, if used for minerals or for coke manufacture, are much smaller, since they are either not combusted or accounted under coke consumption. As a simplification, we therefore assume that all of the 123 Mt CO_2-eq can be removed if coal is removed.

gas emissions, bearing in mind that, under current DECC modelling and announced government policy, the majority of existing coal plants are already expected to be retired by 2025, with the plant capacity remaining expected to be used less and less of the time (below 20% load factor from 2020). The CO_2 savings offered by immediate coal-to-gas switching would therefore only exist for a maximum of 10 years, and if the coal plants are assumed to be used at lower load factors, the potential CO_2 savings will also be lower.

Second, since the new capacity cannot in reality be installed instantly, this 10-year window of opportunity is likely to be even shorter. For comparison, during the first UK dash-for-gas new gas capacity was added at a maximum rate of 5 GW/year and an average of 2.1 GW/year in the ten years between 1991 and 2001. It would therefore take nearly three years to install the 13 GW capacity necessary if this maximum level was to be achieved every year. This extends to at least six years if 30 GW needs to be installed, shortening the window for useful coal-to-gas switching further.

Third, it is necessary to consider the longer-term picture and the risk of carbon lock-in. If investors were encouraged (by whatever mechanism) to either construct or bring out of mothballs the 13 GW CCGT necessary to replace existing coal, they are likely to wish to use these assets to their maximum potential until capital costs are paid off[9]. Modern CCGT plants have a technical lifetime of at least 25 years, though their financial lifetime has usually been shorter than this (typically 15 years for plants built in the 1990s 'dash for gas'). This means that, if economic conditions allow, some new plants that enter service now could be expected to still be producing power in 2040. By this time, annual UK emissions need to be lower than around 215 Mt CO_2-eq. If 13GW of CCGT capacity were still operating at baseload without CCS, these plants would be continuing to produce 34 Mt CO_2-eq every year, and would therefore account for over 15% of the UK's emissions. Policy measures may therefore be needed to address this carbon lock-in risk of coal-to-gas substitution, in order to ensure that any CCGTs that are still required by 2040 are either fitted with CCS or operated at much lower load factors.

The conclusion is that while coal-to-gas switching can be important in principle, there are a number of factors, such as the fact that coal plant retirements are expected in any case, that may limit its usefulness. The main policy priority is, therefore, to put in place the necessary incentives for building gas power plants, which may be needed for replacing coal and/or system flexibility, while ensuring that these incentives are robust to different outcomes so that investments are made when needed.

The scenarios that follow in the next section shed further light on this issue.

[9] To be consistent with 2040 carbon budgets, running hours of new CCGTs would need to be lower than the original baseload load factor, as has been the case with many first generation plants. Due to poor economics, some of the original 'dash for gas' plants from the early 1990s have now been closed, mothballed or converted to run in open cycle mode.

4. Scenarios of future UK gas consumption

4

4. Scenarios of future UK gas consumption

This section turns to the question of how the role of gas in the UK energy system might change in the future, and assesses the extent to which gas can act as a bridging fuel in the UK. To do so, it examines the changes in gas consumption between the different scenarios described in Section 2. First, however, to provide some additional context, it presents some long-term projections of gas use in the UK produced by National Grid.

In our previous analysis examining the global potential for natural gas to act as a bridge to a low-carbon future (McGlade et al. 2014, p.26) we suggested that for it to act as such a bridge, natural gas consumption should rise in both a 'relative' sense and an 'absolute' sense.

- Natural gas acts a 'relative' bridge in a region (or globally) when total consumption is greater in some period in a scenario leading to a 2°C average temperature rise, relative to a scenario that contains no GHG emissions reduction policies.
- Natural gas acts as an 'absolute' bridge in a region (or globally) when total consumption rises above current levels over some period until it reaches a peak and subsequently enters a permanent or terminal decline.

Analogous to this analysis, here we compare scenarios which reach the UK's 80% emissions reduction target for 2050 with those that do not to understand whether or not it can be argued that there is potential for gas to act as a bridge in the UK.

4.1 National Grid

The main long-term view of potential future gas consumption in the UK, apart from the scenarios reported here, is provided by National Grid. It is useful to examine these National Grid scenarios first to provide further context to our scenarios that follow. Its annual "Future Energy Scenarios" publication, first released in 2011, modelled two main scenarios called 'Gone Green' and 'Slow Progression'.[10]

In its latest publication (National Grid 2015), two additional scenarios were examined called 'No Progression' and 'Consumer Power'. These four scenarios were characterised by a variety of economic, political, technological, social and environmental assumptions and collectively form a two-by-two matrix with economic growth and environmental goals (or 'green ambition') on the two axes.

'No Progression' and 'Consumer Power' both have lower green ambitions, but respectively have low and high economic growth rates, while 'Slow Progression' and 'Gone Green' both have high 'green ambitions' and again respectively have low and high economic growth rates.

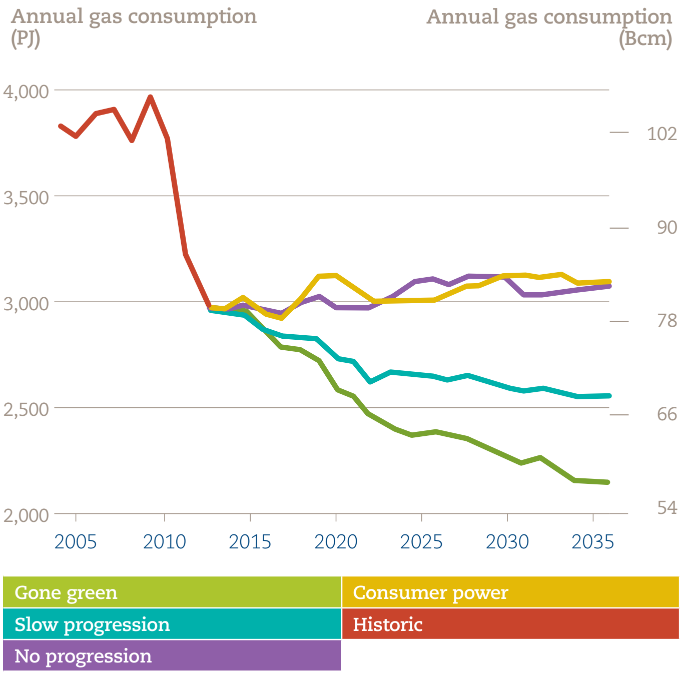
It is worth noting that despite 'Slow Progression' being classified has having higher green ambition, it actually fails to meet the UK's environmental targets: this is because its lower level of economic growth means that environmental policy interventions are more restrained. 'Gone Green' is therefore the only scenario that meets all of the UK's emission reduction targets.

Figure 7 presents gas consumption for the four scenarios from the latest publication. No Progression and Consumer Power both follow similar paths, with gas consumption rising slightly from 2013 levels. In contrast Slow Progression and Green Growth decline continuously to around 15% and 30% below 2013 levels.

There are a number of interesting conclusions apparent from Figure 7. First, in none of these scenarios does consumption return to the level seen in 2012. Second, the more stringent the environmental ambition (e.g. as we move from No Progression to Slow Progression to Gone Green) the lower the level of gas consumed. Third, by 2035 there will still be significant amounts of gas consumed regardless of the future scenario for the UK energy system. Fourth, and finally, changes in economic growth seem to have much less of an effect than green policies (since No Progression and Consumer Power are almost identical).

Regarding the first two of these results, it is evident that the National Grid scenarios do not imply that there is much potential for gas to act as a bridging fuel in the UK. Consumption is always lower than current levels and it is lower than in scenarios that do not meet the UK's

Figure 7: Projections of UK gas consumption from 2015 by National Grid



Source: Modified from National Grid (2015

[10] A third scenario 'Accelerated Growth' was also modelled in the first two National Grid publications in 2011 and 2012. However, this was removed from the 2013 edition onwards.

emission reduction targets (i.e. it is lower in both an absolute and relative sense in all time periods).

Nevertheless, it is important to bear in mind the third result, that even if it cannot be argued that natural gas can act as a bridging fuel, substantial quantities of gas will still be required up to 2035. The fourth result is counter-intuitive given the significant drop in historic emissions (shown in Figure 6) following the financial crisis in 2008. However, given the very tenuous evidence base on the relation between future economic growth and gas consumption in the UK, none of the scenarios we construct using ESME and UKTM include differences in economic growth.

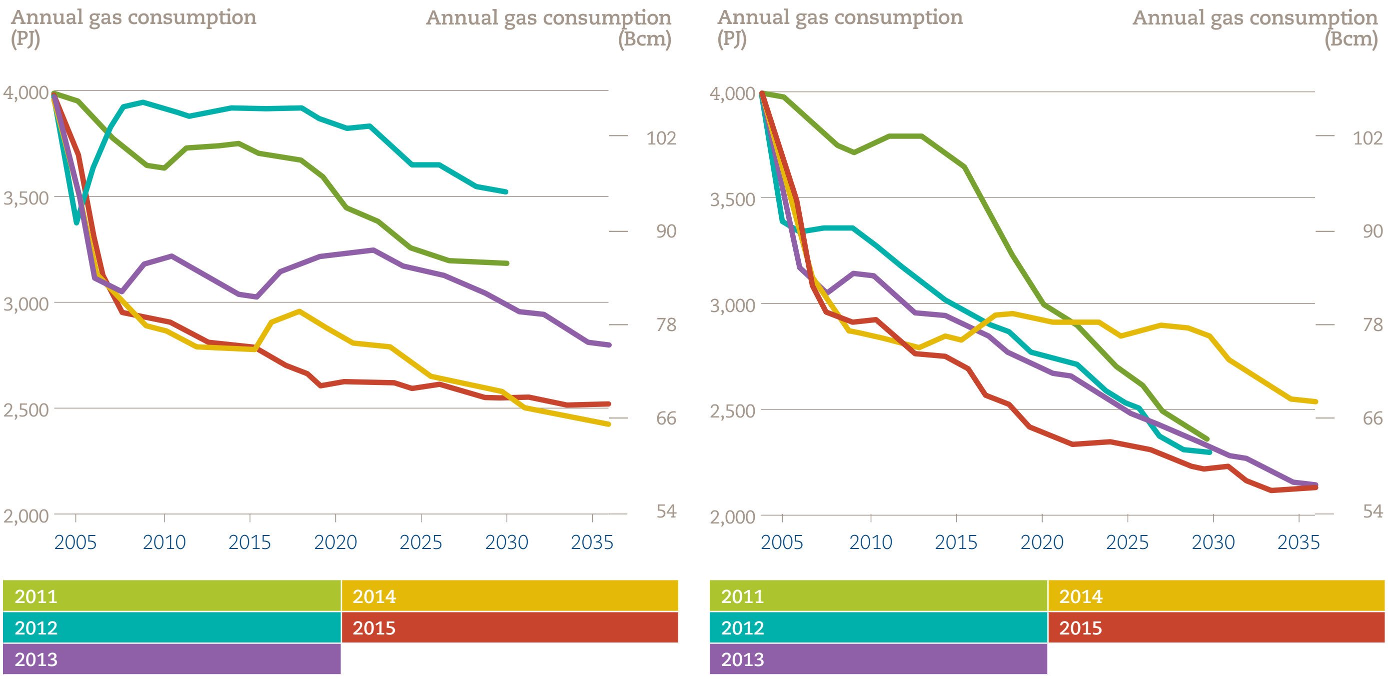
Before moving on to the results from ESME, given there have now been five annual scenario reports from National Grid, it is possible to examine whether there have been any trends over time in the two scenarios that have featured in all. These are presented in Figure 8. It appears that there has been a general trend to reduce projected consumption levels in successive versions of the report, although this is more apparent with Slow Progression than with Gone Green.

There are two exceptions to this: the 2012 Slow Progression projection was around 10% greater than the 2011 projection, but more interesting is the 2014 Gone Green projection. Consumption in this stabilises at just under 3000 PJ (80 Bcm) up to 2030. This is a higher level than had been projected in the three previous Gone Green scenarios, which converged at around 2300 PJ (60 Bcm) in 2030. Indeed, in the 2014 edition, consumption in Gone Green is greater than in Slow Progression from the early 2020s onwards. While this was reversed in the 2015 edition as shown in Figure 7 as well as Figure 7, this does suggest that under certain conditions, additional gas use could be useful for helping the UK meet its emission reduction targets.

To conclude this brief review, despite the 2014 Gone Green outlier, the National Grid scenarios imply that: UK gas consumption is unlikely to grow to any great extent in the future, that meeting the UK's emissions reduction targets will generally result in less gas being consumed in the future, but that there are still substantial levels of gas consumed (greater than 50 Bcm) in all scenarios even out to 2035.

The following sections examine the results from our scenarios described in Section 2. There are a number of reasons why these can provide additional insights to those from the National Grid scenarios including: that they consider a wider range of scenarios and uncertainties, that they contain outlooks to the crucial 2050 timeframe, and that the models used rely on different modelling frameworks and also include a wider range of technology options.

Figure 8: Projections of UK gas consumption in 'Slow Progression' (left) and 'Gone Green' (right) from successive editions of National Grid Future Energy Scenarios publication



Source: Modified from National Grid (2011, 2012, 2013, 2014, 2015)
Note: The 2011 and 2012 editions contained projections to 2030 only

4.2 ESME results

Gas consumption in the three core ESME scenarios is presented in Figure 9 which projects the implications of the uncertainties set out in Table 1. The maximum and minimum of these uncertainty ranges describe the 10th to 90th percentiles of consumption from the 250 runs in each time period i.e. the bottom of the range is defined by consumption in the 25th lowest run and the top by consumption in the 225th lowest (or 25th highest) run.

Median gas consumption in the reference case (that meets the 4th carbon budget) initially falls out to 2020 before rising rapidly between 2030 and 2040 and finishing at 4,250 PJ (115 Bcm), a 10% increase on 2010 levels. The uncertainty spread also grows over time from around 25% of the median value[11] in 2030 to over 60% by 2050.

This level of growth is generally greater than in the National Grid scenarios, discussed in the previous section, that disregard the UK's emissions reduction requirements. Nevertheless, these lie at around the 33rd percentile in 2030 and so are well within the uncertainty range generated by ESME. The median values in the Reference case can also be seen to lie towards the upper end of the uncertainty range especially after 2040, giving a right-skewed probability distribution over the gas consumption in 2040 and 2050 projected by these scenarios.

Figure 10 (left panel) gives the relationship between gas consumption in the Reference scenario and gas prices in 2050 and it can be seen that consumption does not increase much above 4,900 PJ (130 Bcm) regardless of the assumed gas price level. This 'saturation level' occurs because most (>90%) of electricity generation is met by gas, gas provides 65% of household fuel (this could be 5 to 10% higher if there was no penetration of district heating), and all HGVs are converted to run on natural gas. As a result, there is little additional market share that gas can gain.

In the 80% reduction case with CCS, the median consumption initially falls but is then largely flat to 2040 at just over 3100 PJ (around 85 Bcm) before exhibiting a large drop in the final period and thus ending up 40% below 2010 levels. The uncertainty spread up to 2030 is similar to that in the reference case but thereafter it grows rapidly to over 100% by 2050. This rapid growth in uncertainty can be explained by the larger range of new technology options that are available to the model in latter periods (such as conversion to hydrogen, use with CCS in the power sector), but the wide spread in the costs and rates at which these can be built. The changing manner in which gas is used out to 2050 is explored in more detail in the discrete UKTM scenarios below.

Comparing the median of the two scenarios it is again apparent that after 2020, consumption is always lower in the 80% reduction case than in the reference case. Despite the small rise over 2030-2040 in the 'with-CCS' scenario, the predominant downward trend of the median throughout the modelling period suggests that the ESME model finds little potential for gas to act as a bridge in the UK in an optimal trajectory towards a low-carbon energy system.

Nevertheless, it can also be seen that there is significant overlap between the uncertainty distributions for these two scenarios. Indeed, consumption in some of pathways towards the upper end of the distribution in the 80% reduction case with CCS is not significantly lower than 2010 levels. In general, these occur whenever gas prices are low and the technology options that can utilise gas as an input have favourable cost and build rate assumptions. Figure 10 (right panel) indicates that future gas levels in the 80% reduction case are closely (albeit not perfectly) correlated to assumed gas prices. If gas prices remain low (below around 60p/therm out to 2050), and there is sufficient technological innovation, it could be possible for gas consumption in 2050 to be at similar levels to those in 2010 whilst still meeting the UK's emission reduction goals.

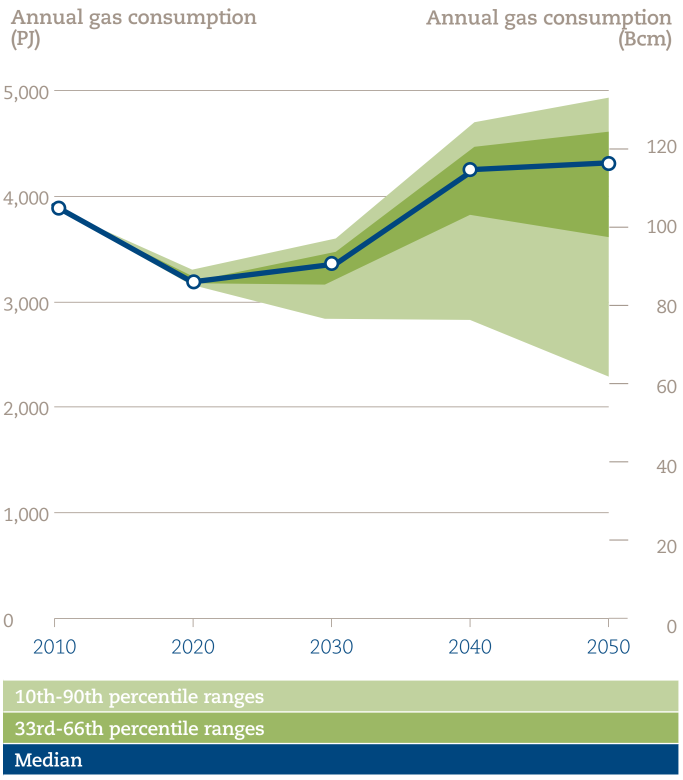
Finally, gas consumption for the 80% reduction case without CCS exhibits a sharp decline over the modelling period, and reaches less than 500 PJ (15 Bcm) by 2050. There is also almost no uncertainty spread despite utilising the same range of uncertainties that were explored in the previous two scenarios. This demonstrates that if CCS is not available, these uncertainties have next to no effect on gas consumption and are effectively redundant. Reaching the UK's emission reduction goals without CCS requires that, despite uncertainties over resource prices, power and end-use sector build rates and investment costs, gas must be steadily phased out over the next 35 years and thus be almost entirely removed from the UK energy system by 2050.

This is not only because gas cannot itself be used with CCS in this scenario, which clearly restricts its use when CO_2 emissions reductions are required, but also because decarbonisation of all secondary and end-use sectors is much harder to achieve without the use of CCS. Sectors that may continue to rely upon unabated gas consumption in the 80% reduction case with CCS therefore have to work additionally hard to reduce emissions. Gas is no longer useful as these sectors must shift to other low or zero carbon sources.

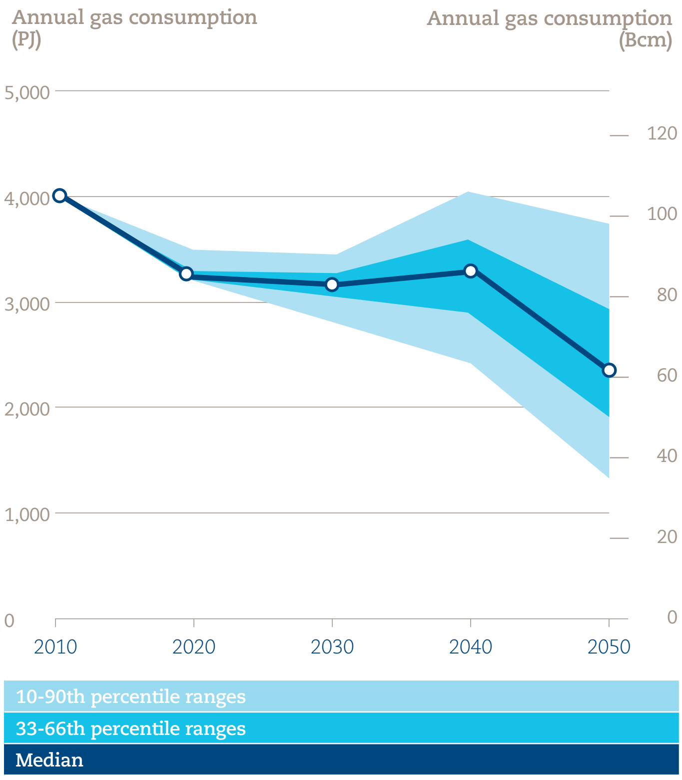
[11] This is calculated by taking the difference between the high and low values and dividing by the median

Figure 9: Projected UK gas consumption in the three core ESME scenarios and relationship between consumption in 2050 and gas prices in the 80% reduction case.

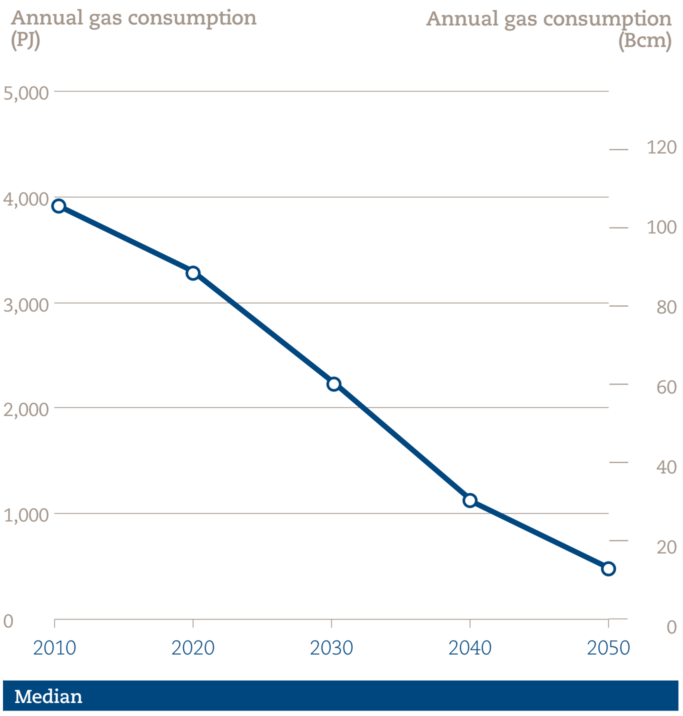
Reference case
(only meeting the 4th carbon budget).



80% reduction case with CCS.

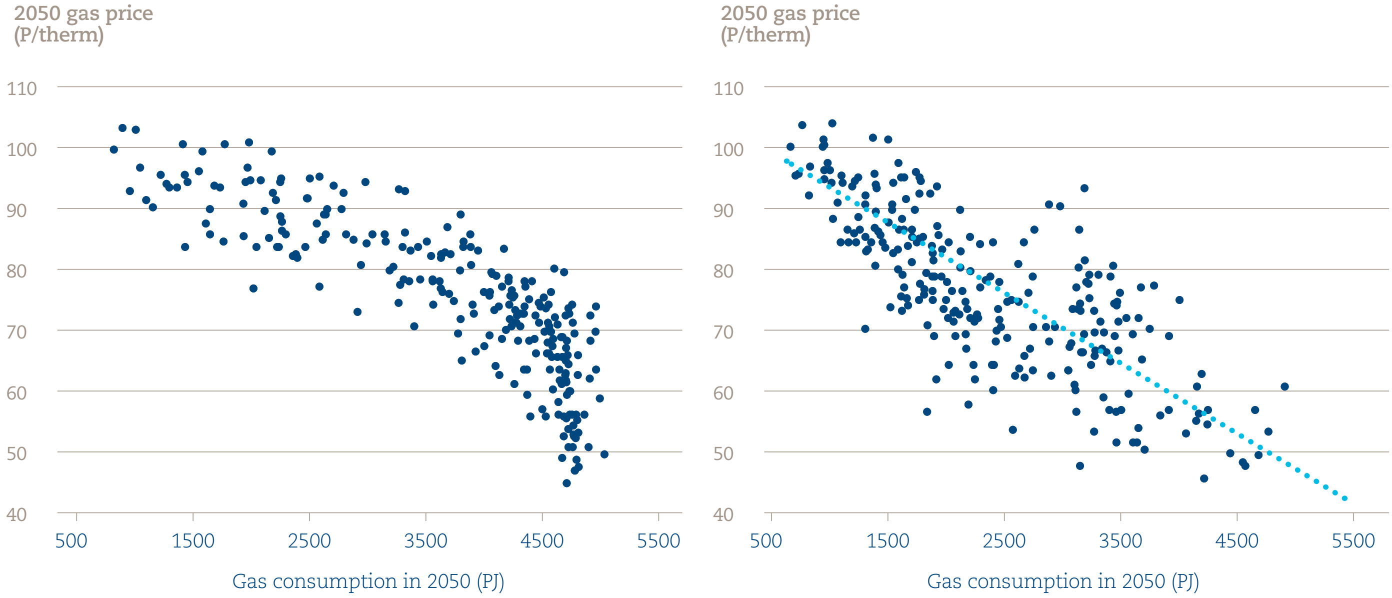


80% reduction case without CCS.



Note: Top left: reference case (only meeting the 4th carbon budget). Top right: 80% reduction case with CCS. Bottom: 80% reduction case without CCS. In all cases, the light shaded areas represent the 10th to 90th percentile ranges, dark shaded areas the 33rd to 66th percentile ranges, and solid lines the medians.

Figure 10: Relationship between consumption and gas prices in 2050 in the reference (left) and 80% reduction with CCS cases (right).



Note: These figures include all 250 projections, with a linear line of best fit plotted for the 80% reduction case (right panel).

4.3 UKTM results

It is easiest to examine the detail of the differences in the use of gas over time and between scenarios using the discrete runs implemented in UKTM. In this section we focus initially on the three scenarios that miss the long-term 80% reduction goal (Section 4.3.1), and then turn to those that meet this goal (Section 4.3.2), and then compare these to examine the extent to which gas can act as a bridging fuel in Section 4.3.3.

4.3.1 Scenarios that miss emissions reduction goals

Figure 11 and Figure 12 present the changes in primary energy consumption and sectoral changes in gas consumption in the **Abandon**, **Insular**, and **Affordable** scenarios: those that are not required to reduce emissions by 80% by 2050. Primary energy consumption in all scenarios in 2030 is at least 22% lower than in 2010, although it then stays relatively constant in each scenario thereafter.

Abandon exhibits the smallest change in overall primary energy consumption, with the largest change the reduction in coal consumption. **Abandon** also has the smallest changes in gas consumption and in the way that gas is consumed. Indeed despite dropping by nearly 20% between 2010 and 2015, gas consumption after 2015 remains broadly constant. There is a reduction in use in centralised gas generation over time, but this loss is compensated for by an increase in the use of combined heat and power (CHP) units in both the residential and industrial sectors. As a result gas use in the residential sector actually increases steadily from 2015 onwards, the only scenario in which this occurs.

In 2030 primary energy consumption in **Affordable** is relatively similar to that in **Abandon** with slightly reduced coal consumption and higher levels of renewables and nuclear, but these differences are small. Indeed, the largest difference is in gas consumption, which exhibits a more steady decrease over time despite the availability of cheap gas. Use in the electricity sector initially falls only slightly as 10 GW of new CCGT capacity is constructed during the 2020s. However, as the need for a 60% reduction in emissions by 2050 is most cost-effectively met by the decarbonisation of electricity, existing gas capacity is retired and is not replaced. The carbon intensity of centralised generation falls from 430 gCO_2/kWh in 2015 to 225 gCO_2/kWh by 2030, before dropping rapidly to 30 gCO_2/kWh in 2040 and turning slightly negative thereafter. Consequently, between 2030 and 2050 gas use in centralised generation exhibits the largest drop seen in any sector. In the residential sector there is a 1%/year average decline in gas use made possible initially through efficiency measures and latterly by a small degree of electrification of heat.

Figure 11: Primary energy consumption in UKTM scenarios failing to meet 2050 carbon targets

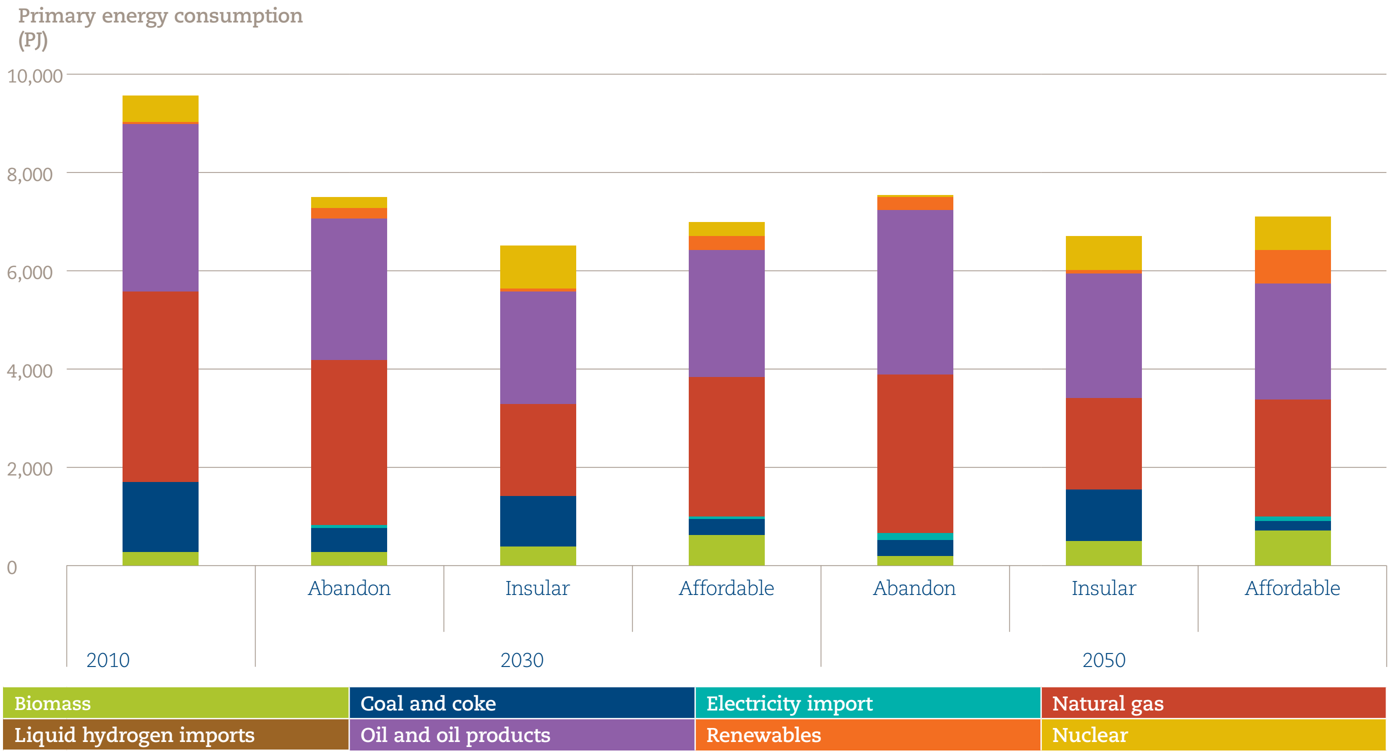
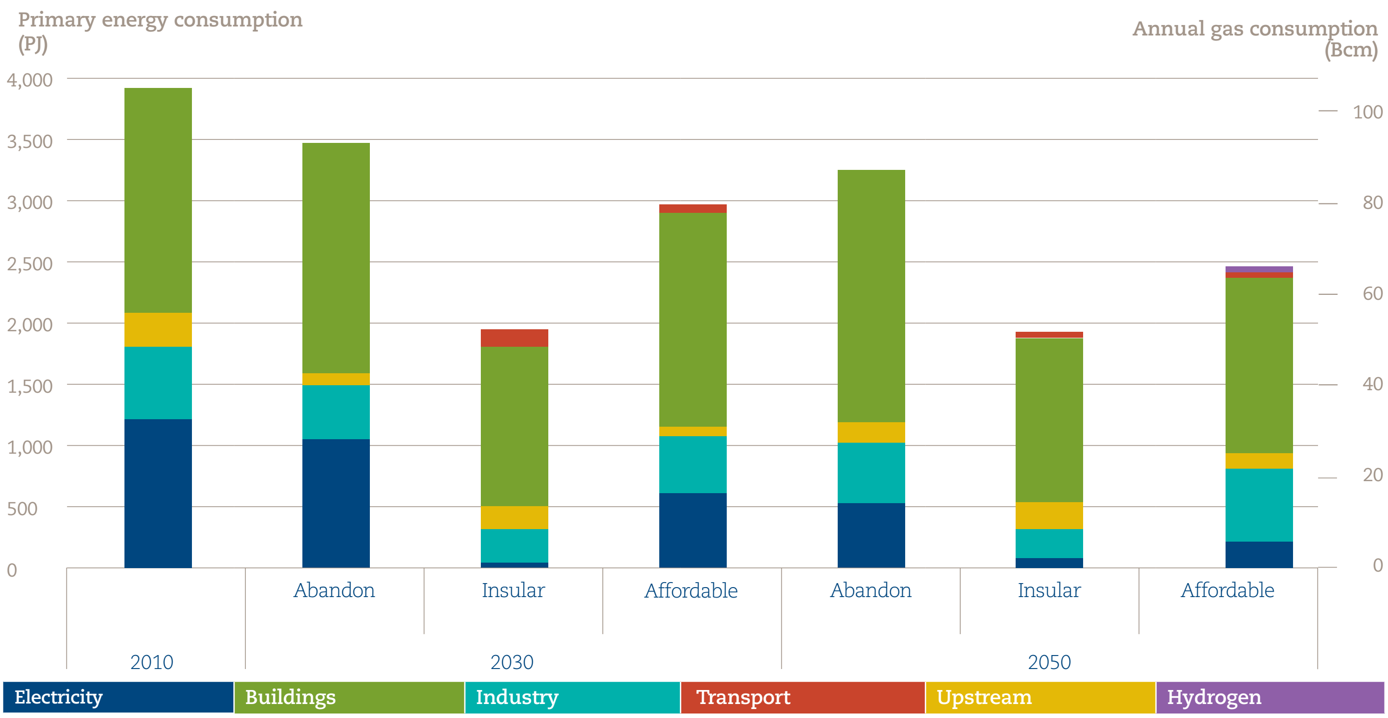


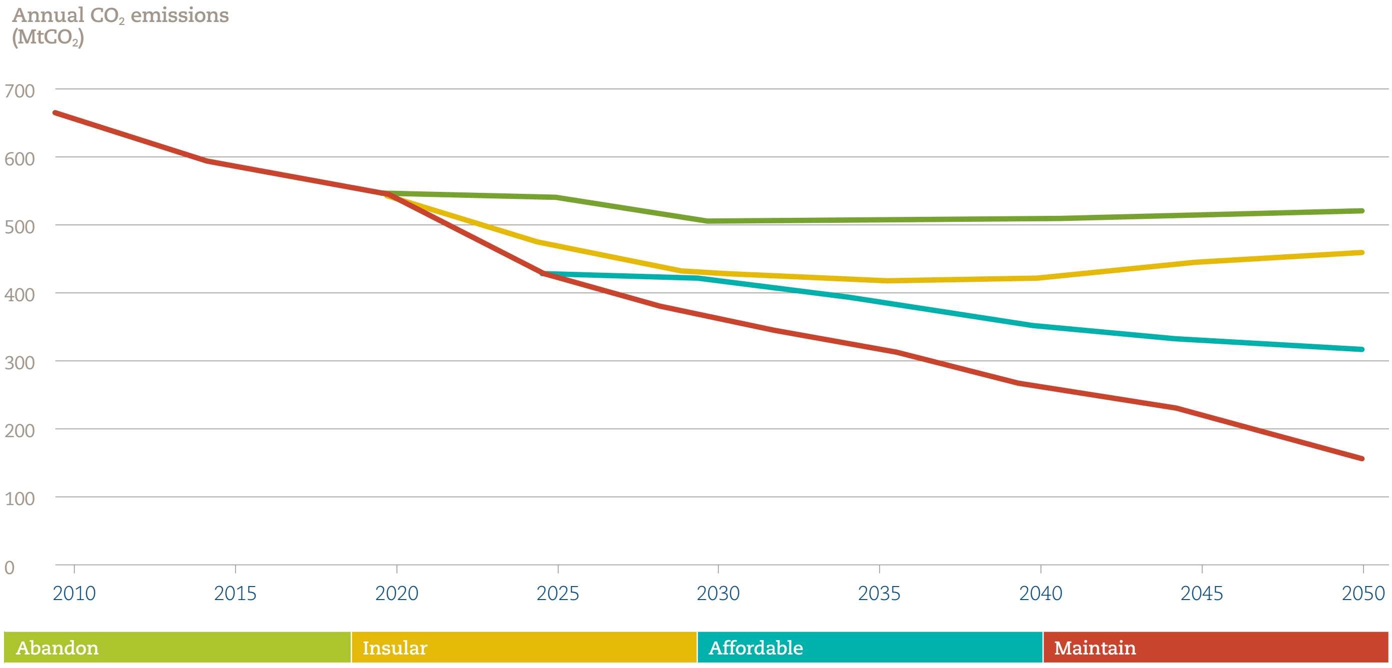
Figure 12: Sectoral gas use in UKTM scenarios failing to meet 2050 carbon targets



Insular displays the largest changes of the three scenarios in both 2030 and 2050. Given the need to rely predominantly on domestic sources of energy production in this scenario, there is a much greater (and rapid) uptake in efficiency measures. Primary energy consumption is therefore 15% lower than in **Abandon** in 2030. Coal consumption can be seen to be significantly different, and indeed this is the only scenario in which coal maintains its current share of primary energy consumption of around 15% throughout the model horizon; in all other scenarios coal drops to less than 5% by 2030 (and less than 2% in the **Maintain** scenarios discussed in the next section). Between 2010 and 2030 total gas use falls by 50%, with gas entirely removed from the electricity sector, and residential sector consumption dropping by nearly 30%. After 2030, annual consumption stagnates at around 2000 PJ (55 Bcm) with all sectors continuing to maintain their levels of consumption.

Figure 13 displays the changes in resultant outlook for total GHG emissions in these scenarios given these changes compared with emissions from Maintain (discussed below). Abandon shows a marginal reduction in emissions after meeting the 3rd carbon budget requirements (for total emissions to be less than 550 Mt CO_2-eq in 2020). However, it is clear that allowing no new centralised coal power plants (one of the key assumptions in Abandon as shown in Table 2) is far from sufficient to lead to a reduction in GHG emissions. Affordable exhibits a large drop in 2025 as it seeks to meet the 4th carbon budget and thereafter has an average annual decline in emissions of just over 1%. Interestingly, in 2030, Affordable and Insular have a very similar level of emissions at around 425 Mt CO_2-eq. Emissions have therefore dropped by 25% between 2020 and 2030 despite no explicit requirement for them to do so. The policy goal of limiting imports within these scenarios has led to emissions reductions in the medium-term. However, given the continued reliance on coal in power generation in these scenarios, this is clearly insufficient for meeting medium-term goals that are optimally consistent with long-term objectives (as discussed below).

Figure 13: CO_2 emissions in **Abandon**, **Affordable**, **Insular**, and **Maintain**



4.3.2 Focus on 80% reduction targets

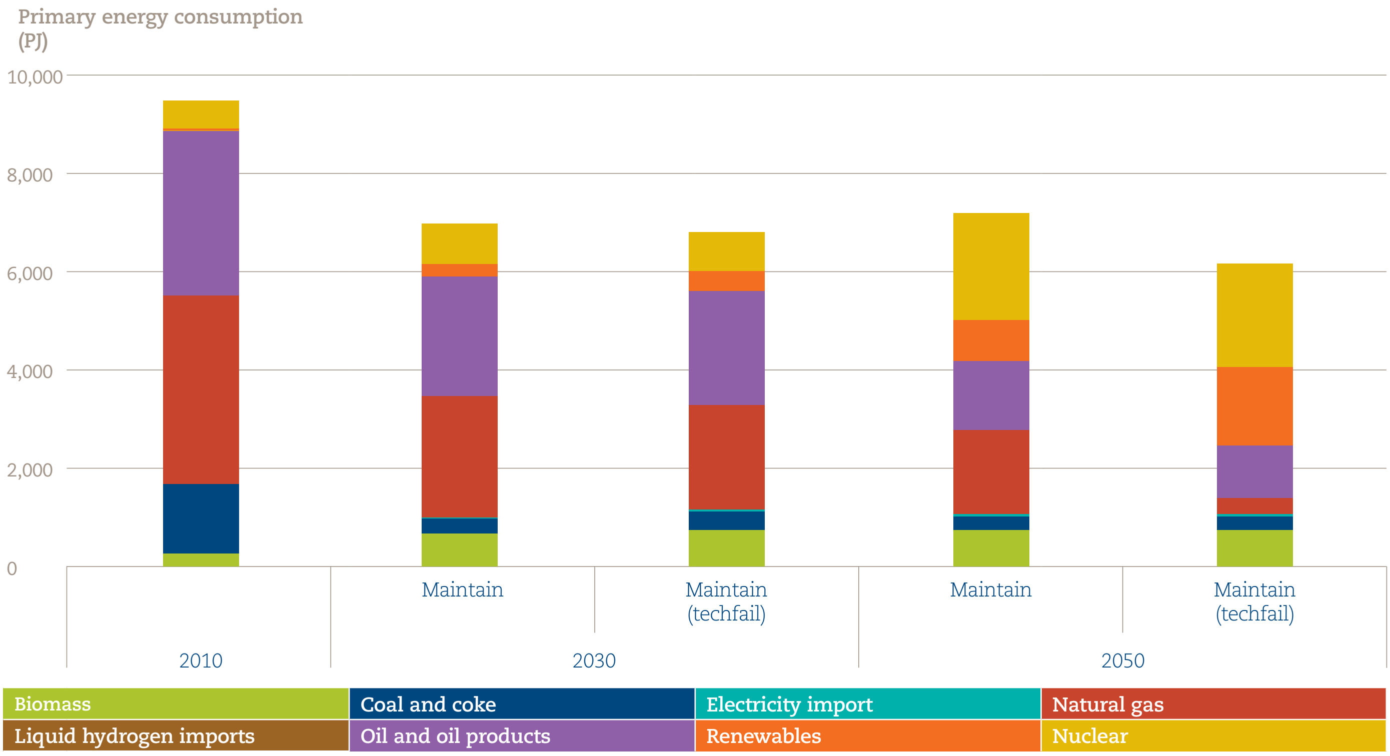
Figure 14 and Figure 15 next display primary energy consumption and sectoral gas consumption in the two core scenarios that meet the UK's long-term emission reduction targets. Over the medium-term differences in energy consumption between these two scenarios and between the scenarios described above do not appear too large. For example, primary energy consumption in 2030 in both scenarios is 27% below 2010 levels, broadly similar to the reduction in **Affordable** and at a greater level than was seen in **Insular**. Indeed, it is unsurprising that **Maintain** and **Maintain (tech fail)** are not so different in 2030 because the only difference between them, carbon capture and storage, is assumed only to become available in **Maintain** in 2025. Coal is effectively eliminated in both scenarios. The construction of Hinckley C (3.2 GW) prior to 2025 and an additional 5 GW nuclear constructed by 2030 means that there is a 40% growth in nuclear electricity between 2010 and 2030 despite the retirement of a large portion of the existing nuclear fleet. Emissions to 2030 in these two scenarios (both follow an identical path as shown for **Maintain** in Figure 13), are lower than in the other three scenarios, particularly **Abandon**. With increased uptake of efficiency measures in buildings, a shift to hydrogen and gas use in heavy goods vehicles (see below), and the increased use of nuclear electricity rather than gas (as in **Abandon** and **Affordable**) or coal (as in **Insular**), all sectors contribute to this relative difference.

Turning to gas consumption, between 2010 and 2030, 60% of the drop seen in both scenarios results from falls in the electricity sector, with smaller drops in industry (accounting for 15% of the total drop) and residential (20%). A small increase in the use of gas in transport can also be seen in both scenarios in the medium term, reaching a maximum of 100 PJ in **Maintain** and 170 PJ in **Maintain (tech fail)**. In both cases there is some uptake of CNG in Light (LGV) and Heavy Goods Vehicles (HGV). This is also seen in **Affordable** but not in either of the other two non-80% reduction scenarios. Indeed at its peak nearly 35% of HGVs are CNG in **Maintain** and nearly 60% in **Maintain (tech fail)**. In both of these scenarios, this growth in CNG occurs while the technology market for Hydrogen matures. By 2050 in both scenarios, all HGV service demands are satisfied by Hydrogen.

Since consumption of gas in freight transport grows in both **Maintain** scenarios out to 2040, compared with both 2010 and **Abandon**, it could therefore be reasonable to argue that natural gas can act as a bridge in the freight sector.

Over the long-term to 2050, there are much starker differences both between these two scenarios and with the scenarios described above. Similar to what was seen in the ESME scenarios above, it is clear that without CCS gas is again almost entirely removed from the UK energy system. What remains in **Maintain (tech fail)** is predominantly used in industry (most of which is as a petrochemical feedstock or in non-energy uses) and as back up to the intermittency of renewables in the power sector (installed gas capacity is used at less than 5% load

Figure 14: Primary energy consumption in UKTM scenarios that meet the UK's 2050 carbon targets



factor). Overall consumption is less than 450 PJ (12 Bcm), a 90% reduction on 2010 levels.

In **Maintain**, there is a significant decrease in residential sector (see below) consumption but this is largely compensated for by the growth of an entirely new industry, namely the steam methane reforming (SMR) of natural gas to produce hydrogen. Crucially, this SMR is carried out in combination with CCS so that the overall level of emissions that occurs is vastly reduced. Hydrogen in this context provides a useful vector for decarbonising decentralised service demands, predominantly transport (as discussed above) and industry, in approximately equal proportions. This technology is entirely absent in all other scenarios examined demonstrating the necessity of both emission reduction goals, and the availability of CCS if it is to have any role in the future UK energy system.

There again continues to be some use of gas in the electricity sector, both as back up to renewable intermittency and as centralised CCS plant, although with only 2 GW gas CCS capacity installed in the final period, this latter role is marginal. There is also continued reliance (around 300 PJ or 8 Bcm) on gas in industry, although as above, the majority of this is as use as a feedstock for petrochemicals and in non-energy uses. The emergence of hydrogen in the industry sector in latter periods impinges on the use of gas, as well the use of biomass, which is more usefully deployed elsewhere.

As noted, gas use in the residential and service sectors (Buildings in Figure 14) exhibit a rapid decline between 2030 and 2050 in this scenario. Indeed it is only after 2035, as the 80% target becomes increasingly difficult to meet, that the majority of changes occur in the use of gas in buildings.

This is shown in more detail in Figure 16, which provides relative changes in consumption over time in **Maintain** and **Abandon** in the buildings and electricity sectors. As has been noted above, in initial periods (up to 2025) consumption in both sectors in both scenarios is broadly similar. However between 2025 and 2030 there is a large reduction in gas consumption in **Maintain** in the electricity sector, while consumption in the residential sector remains broadly flat. Only in 2035 is there a shift in gas use in the building sector, which then falls at an average of 7%/year for the next 15 years. The long-term contrasts with **Abandon** are also evident: as noted above, there are steady reductions in the electricity sector gas use after 2030 – albeit at less than half the rate seen in the buildings sector in **Maintain** – and building sector use actually grows steadily. Indeed, comparing these results with the National Grid scenarios, it is worth noting that up to 2035 (the time horizon of the National Grid scenarios), consumption in **Maintain** is generally around 10-20% higher than the levels in the National Grid's latest Gone Green scenario. The main difference arises from this continued reliance on gas for heat in buildings.

Figure 15: Sectoral gas use in UKTM scenarios that meet the UK's 2050 carbon targets

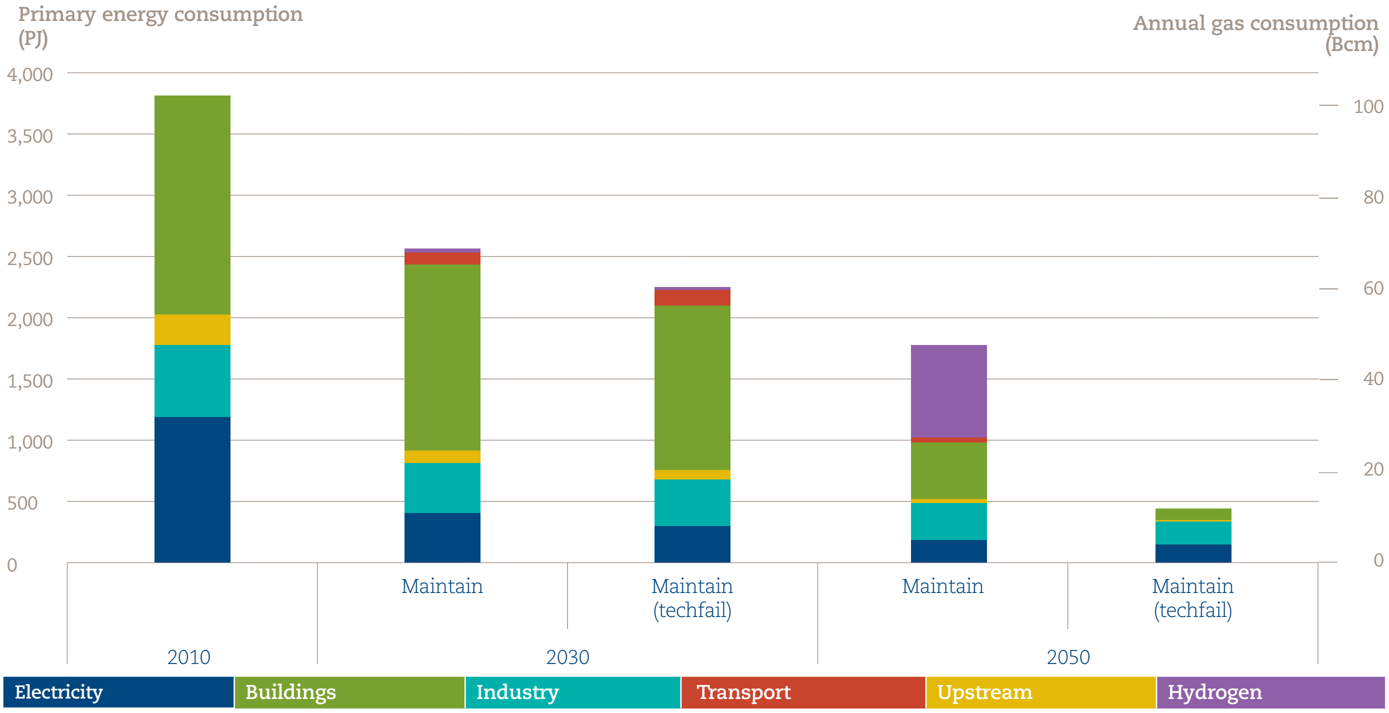
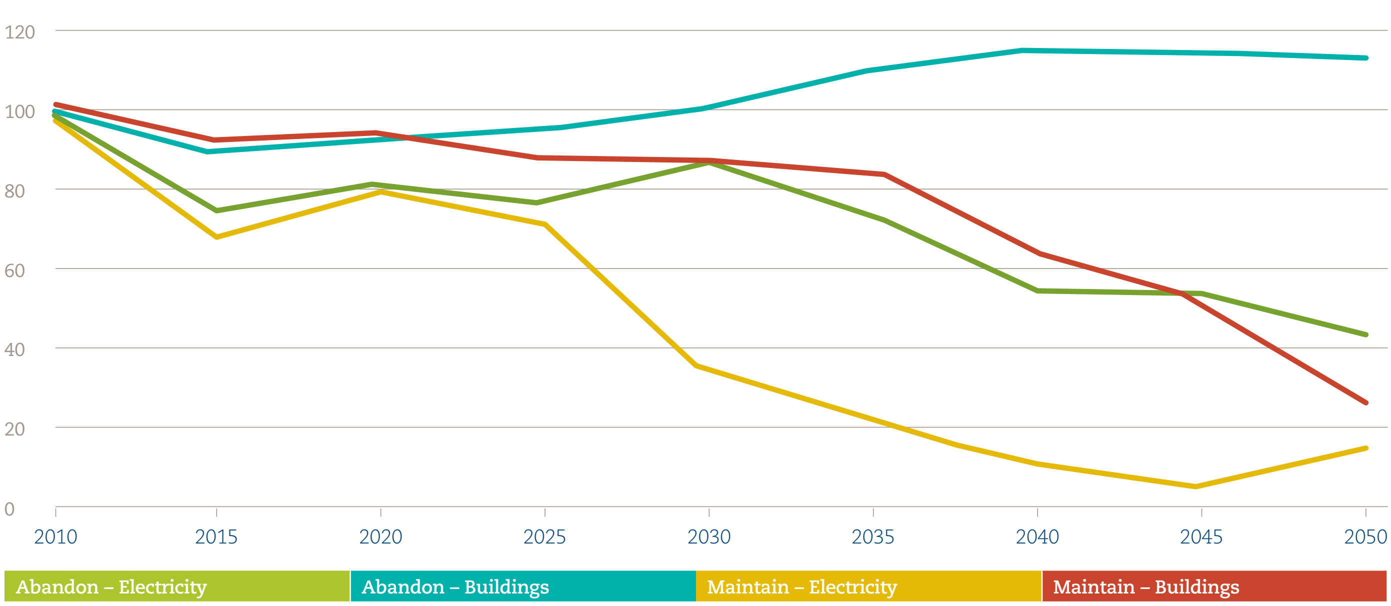


Figure 16: Relative changes in gas use in electricity and buildings in **Abandon** and **Maintain**



This delayed action in respect of buildings poses challenges for emissions reduction policies. Continued use of gas is a very cost-effective way to provide heating in buildings, not least because all the necessary infrastructure has already been deployed over the past number of decades. Shifting to an alternative energy source is likely to require huge investment in new infrastructure, new technologies, and the development of new markets. It is apparent that these alternatives are cost- effective only at higher CO_2 prices (i.e. when the reduction targets are increasingly stringent) and so only start to be adopted at a significant scale after 2035.

Replacing nearly all of the gas used in buildings with alternatives, including with district heating but more significantly heat pumps, within a 15-year period is in reality extremely ambitious, and would require significant development of infrastructure and market capacity beforehand to achieve.

In reality, it is likely that the transition away from the consumption of gas in buildings will need to be underway in the mid-2020s.

Given the scale of ambition, it is unlikely that gas will be removed, and hence emissions reduced, from the buildings sector by market forces alone. A combination of regulatory mechanisms in combination with market incentives will be required if policy makers want to decarbonise energy use in buildings over the medium and longer term.

4.3.3 Gas as a bridge

We can use the above UKTM results to address the question as to whether or not gas can act as a bridging fuel towards a low-carbon UK energy system, and to look more generally at coal-to-gas switching in the power sector.

With the emphasis placed on domestic sources of energy in **Insular**, and the consequent re-opening of UK coal mines, new coal generation capacity is constructed. It is clear therefore that there is no coal-to-gas switching in this scenario. This is the only scenario in which new coal plants are opened. In all other scenarios, regardless of the emission reduction goal or price of fossil fuels, coal has been eliminated from the electricity sector by 2030.

Coal use in the electricity sector continues in the **Maintain** scenarios at an identical level to **Abandon** and **Affordable** up to 2020, despite differing levels of gas capacity installed and levels of gas consumption. The absence of any decline in coal consumption between these scenarios suggests that coal-to-gas switching is not cost-effective prior to 2020.

After 2020, however, the four scenarios display differing behaviour. **Abandon** continues to sweat the coal assets for as long as possible, until they are retired. In the other three scenarios, there is an almost immediate cessation of coal use in the power sector in 2025, and significant construction of new CCGT capacity throughout the 2020s (7.5 GW in **Maintain (tech fail)**, 10 GW in **Maintain**, and 22 GW in **Affordable**). Despite this new plant, and the loss of close to 200 PJ (55 TWh) of electricity from coal plants,

There is practically no potential for gas to act as a bridge to a low-carbon economy in the UK

levels of generation from gas (and gas consumption) remain broadly flat in both **Maintain** scenarios. There are increases in production by wind, a greater level of imports through interconnectors, and the use of biomass in CHP, but efficiency measures account for the largest share of the drop in electricity generation from coal. There is, in contrast, an increase in electricity from gas in **Affordable**, which alone offsets around 50% of the reduction in generation from coal.

In the scenarios that meet the UK's climate objectives, these results therefore suggest that while it is cost-effective to construct some new efficient CCGT plants, this mainly serves to replace existing coal and CCGT plant. Coal-to-efficiency and coal-to-renewables is found to be a more cost-effective solution than coal-to-gas substitution. Since **Affordable**, which fails to meet the long-term 80% reduction target, has a much greater level of coal-to-gas switching, this highlights a potential risk of relying predominantly on coal-to-gas switching in the power sector to meet the 2025 emissions reductions.

There is also a steady decrease in the load factor of newly installed CCGTs in **Maintain**, from over 90% for the first ten years after they are first constructed in the early 2020s to around 60% in 2035, 15% in 2040, and 5% for the last five years of their lives. Since UKTM is a cost-optimising model, the gas capacities installed are not stranded assets from a system perspective. But the load factors suggested in **Maintain** introduce significant uncertainties for potential individual investors in CCGT plants over the returns on their investment they could expect, which would depend heavily on market prices and the framework of investment incentives, such as the availability of capacity payments. If more than the 10 GW capacity that exists in **Maintain** in 2040 were to be constructed over the next twenty-five years, then these will clearly have to operate at even lower load factors to be consistent with carbon emissions reduction targets, increasing the importance, to secure the necessary investments, of having a strong investment framework underpinned by public policy with long-term credibility.

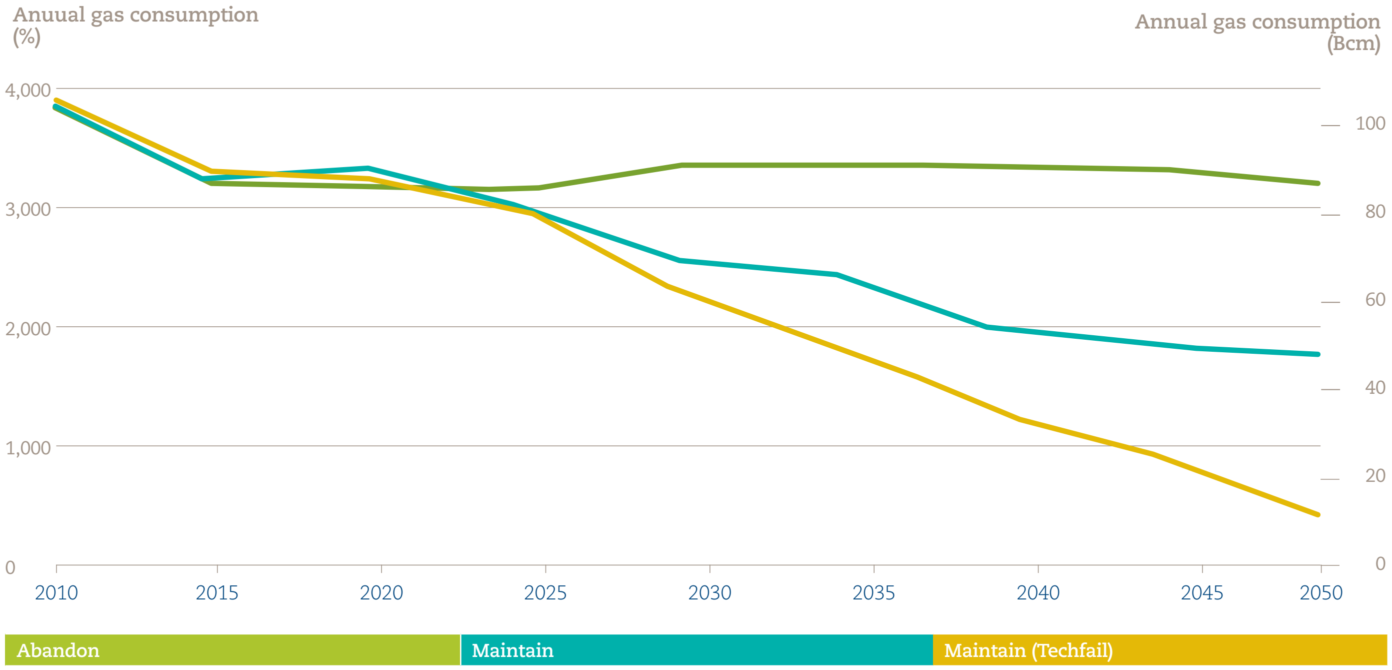
These low load factors highlight the risk of implementing an uncontrolled new 'dash-for-gas', not just to investors, but also to meeting the carbon targets, as gas generators might resist the load factor reductions unless these had been explicitly factored into their investment incentives from the start.

In conclusion, while it may be a 'no-brainer' that coal-fired power plants should be shut as soon as possible to reduce emissions if the UK is serious about maintaining its long-term commitments to emission reduction, it is not necessarily a no-brainer that new gas plant should be the replacement for these.

Figure 17, which shows total gas consumption over time in **Abandon**, **Maintain**, and **Maintain (tech fail)**, can help provide an answer to the question as to whether or not gas can act as a bridging fuel in the UK. Despite a small rise (<3%) in **Maintain** between 2015 and 2020, and a very slightly higher level of consumption (<4%) in the 2020s in **Maintain** compared with **Abandon**, gas consumption is lower in **Maintain** in all subsequent periods and falls continuously from 2020.

Looking back to the requirements to classify gas as a bridge set out earlier, it is apparent that gas acts as both a relative and absolute bridge only over 2015-20. Thereafter it soon falls below the level of gas consumption in both **Abandon** and in 2010. However, given that the absolute and relative increases in consumption between 2015 and 2020 are so slight, and since neither the ESME nor National Grid scenarios exhibited any similar such increases, we conclude that, on our definitions of the term, there is practically no potential for gas to act as a bridge to a low-carbon economy in the UK. This is with the exception of some specific niche sectors such as freight, where, as discussed above, results suggest that gas could perform a useful bridging role, even though the volumes involved in such sectors will be relatively small.

Figure 17: Gas consumption over time in **Abandon**, **Maintain**, and **Maintain (techfail)**



As shown by the analysis in Section 3, we believe gas has already acted as a bridging fuel in the UK to a considerable extent, accounting for nearly all the 20% drop in emissions witnessed between 1970 and 2000. While it is now time for truly low and zero-carbon sources of energy (including efficiency and demand reduction) to come to the fore if the UK's carbon targets are to be met cost-effectively, it is nevertheless evident that gas consumption remains significant in all cases that meet the 80% reduction target in 2050 (although very importantly only if CCS is available as shown in Figure 17). Rather than classifying natural gas as a bridge to a low-carbon future in the UK, it would perhaps better be identified as a stopgap: gas has already acted as a bridge to the relatively low-carbon present. Unless CCS technologies are widely deployed, its future role will be more a diminishing one of filling an ever smaller gap between energy demand and other sources of low or zero carbon supply.

5. Discussion and conclusions

If all coal-fired power generation is to be removed by 2025, and the Government is no longer willing to support the development of CCS, policy makers must think very carefully about how best to replace that capacity

5. Discussions and conclusions

This report has explored the potential future role of natural gas in the UK's energy system. First, by way of setting the context, the historical role of coal-to-gas fuel substitution was examined to identify how much of the 'decarbonising opportunity' remains. Second, we explored National Grid's Future Energy Scenarios and carried out our own modelling exercises – using ESME and UKTM – to explore the sensitivities around future gas consumption and the UK's decarbonisation ambitions. This final section highlights our findings and explores their policy consequences.

Our historical analysis makes it clear that coal-to-gas substitution has already played a major role in reducing the UK's carbon emissions. In fact, the UK is unusual in not having increased its reliance on coal-fired generation in recent decades. The UK is therefore already some way across the coal-to-gas 'bridge'. Nonetheless, coal still plays a significant role in the UK's energy mix, accounting for over 16% of primary energy consumption and 28 % of electricity generation in 2014. However, the UK's commitment to reduce carbon emission by 80% by 2050 (with a series of carbon budgets to guide progress) means that it not a straightforward question of replacing the remaining coal-fired generation (which the Government is now committed to removing by 2025) with new gas-fired capacity, in what some might call a 'second dash' for gas.

Our modelling effort explores the complexities around the future role of natural gas in the power generation sector and in the wider energy system: it is important to remember that the majority of the UK's gas demand lies outside of electricity generation. Our various scenarios explore varying commitments to decarbonisation and also the consequences of the availability, or not, of CCS for gas-fired power and industry. The results of our research are explained in detail in previous sections of this report.

Here our remarks are confined to the assumption that the UK retains its commitment to the current 80% emissions reduction target by 2050, and that coal is removed from power generation by 2025. This was already the direction of travel prior to the recent Government announcement.

Both the ESME modelling and the UKTM **Maintain** and **Maintain (tech fail)** scenarios make it clear that meeting the 2050 target will constrain the role for natural gas in the UK's energy system in the 2020s and beyond. The nature of that role is dependent on other developments in the wider energy system—such as new nuclear, the rate of energy efficiency improvement and the scale of renewable energy—and the availability of key technologies. The ESME results make clear the significance of CCS to keeping gas in the power generation and certain sectors of industry. Without CCS gas must be steadily phased out over the next 35 years and almost entirely removed by 2050. This represents a major challenge in relation to the decarbonisation of domestic heat and undermines the economic logic of investing in new CCGT gas power generation capacity.

The **Maintain** and **Maintain (tech fail)** scenarios see a significant drop in the role of gas in the electricity sector (60%) and smaller drops in industry and the residential sector in the 2020s. It is only in the 2030s and beyond that the two scenarios differ significantly. The absence of CCS in tech fail—in keeping with the ESME results—means that gas must eventually be almost entirely removed from the energy system. What remains is used by industry and sparingly as back-up to renewable intermittency. Interestingly, the **Maintain** scenario keeps a significant amount of gas with CCS in the mix by finding a new role for it in the production of hydrogen. In the **Maintain** scenario, in addition to gas being used as a back-up for intermittency, the availability of CCS permits some centralised CCS plant, and gas is used as a feedstock in industry. This scenario suggests that under certain conditions a significant amount of gas consumption (40-50 Bcm) can still be compatible with the 2050 target.

A 'second dash for gas' may provide some short term gains in reducing emissions. However, this may not be the most cost-effective way to reduce emissions and, in the absence of CCS technologies, it may well compromise the UK's decarbonisation ambitions

Our analysis makes clear that determining the future role for gas in the UK is not a straightforward matter. A simple decision to shut down all coal-fired power generation by 2025 and build a new fleet of CCGT gas-fired power stations could be problematic as it could 'lock in' a significant amount of gas-fired capacity that would only be able to operate at very low load factors in the 2030s and beyond, unless they are retrofitted with CCS. It is questionable whether or not investors could be persuaded to build this capacity without very strong policy incentives, if load factors were even lower than they are now. Incentivising them to do so might not be the most cost-efficient solution. Those resources (the cost of which would ultimately end up on consumer bills) might be better used by replacing that lost coal capacity with additional energy efficiency and demand reduction measures and/or additional renewable energy capacity. The analysis also makes clear the centrality of CCS to retaining gas in the power generation mix and certain sectors of industry. Without CCS demand falls dramatically in the 2030s and beyond, making it even harder to justify investing in new gas- fired power generation.

Two final notes of caution: First, timing is everything. Delays in commissioning a new fleet of nuclear power stations and/or a slow-down in the deployment of renewable forms of energy—particularly in a context of no coal-fired generation after 2025—may increase the future role of gas to levels that are not compatible with the existing carbon budgets, particularly in the absence of CCS. Thus, what happens in the 2020s is critical in determining the path of the UK's energy system in the 2030s and beyond. It is important to avoid a high carbon 'lock in' that would either cause carbon targets to be missed or leave significant amounts of infrastructure stranded.

Second, our scenarios show that the UK debate should not be reduced to a choice between a future with gas and a future without it. Our **Maintain** scenario demonstrates that a significant amount of natural gas can still be consumed beyond 2030—though natural gas plays a different role than it does today. The real challenge is managing a 'soft landing' for the gas-fired power generation sector that keeps sufficient capacity in the mix as its role changes. In addition, alternatives to the use of gas outside the power sector, particularly in heating homes, need to be explored urgently. It is not clear that current policies will achieve this, which highlights the lack of a clear vision of the future role for gas in the UK's low carbon energy system.

This report has not addressed the question of where the UK's gas supply will come from in the future. While falling UK gas demand and access to a diverse range of sources of gas might ease concerns about energy security and import dependence, it does raise questions about the economic cost of maintaining the current infrastructure that is designed to handle significantly higher volumes of natural gas than are likely to be consumed in future.Thus, the focus of gas security could shift away from physical security of supply—where there is more the sufficient infrastructure capacity—to ensuring that sufficient investment is made domestically to ensure that the gas industry can respond to its changing role in the energy mix.

The take-home message from this report is clear. If all coal-fired power generation is to be removed by 2025, and the Government is no longer willing to support the development of CCS, policy makers must think very carefully about how best to replace that capacity. A 'second dash for gas' may provide some short term gains in reducing emissions. However, this may not be the most cost-effective way to reduce emissions and, in the absence of CCS technologies, it may well compromise the UK's decarbonisation ambitions.

References

Balcombe, P. et al., 2015. Methane and CO_2 emissions from the natural gas supply chain. London: Sustainable Gas Institute, Imperial College.

BP, 2015. BP statistical review of world energy, London, UK.

Bradshaw, M. et al., 2014. The UK's Global Gas Challenge - Research Report, London, UK. Available at: http://www.ukerc.ac.uk/asset/F4F59C91-7824-4BEF-88FB1A9A11B18528/.

Bradshaw, M J (2016) 'Unconventional Gas in the United Kingdom.' In Risks, Rewards and Regulation on Unconventional Gas, Edited by Q. Grafton, I. Cronshaw and M. Moore (eds). Cambridge: CUP, in press

CCC, 2008. Building a low-carbon economy – the UK's contribution to tackling climate change, London, UK. Available at: https://www.theccc.org.uk/publication/building-a-low-carbon-economy-the-uks-contribution-to-tackling-climate-change-2/.

CCC, 2013. Meeting Carbon Budgets – 2013 Progress Report to Parliament, London, UK. Available at: https://www.theccc.org.uk/publication/2013-progress-report/.

CCC, 2010. The Fourth Carbon Budget — Reducing emissions through the 2020s, London, UK. Available at: http://www.theccc.org.uk/publication/the-fourth-carbon-budget-reducing-emissions-through-the-2020s-2/.

Daly, H.E. et al., 2015. Indirect CO_2 Emission Implications of Energy System Pathways: Linking IO and TIMES Models for the UK. Environmental Science & Technology, 49(17), pp.10701–10709. Available at: http://dx.doi.org/10.1021/acs.est.5b01020.

DECC, 2015a. Digest of UK Energy Statistics (DUKES), London, UK.

DECC, 2014. Fossil fuel price projections: 2014, London, UK.

DECC, 2015b. Quarterly energy prices: December 2015, London, UK.

DECC, 2011. The Carbon Plan, London, UK. Available at: www.gov.uk/government/publications/the-carbon-plan-reducing-greenhouse-gas-emissions--2.

DECC/Ogem, 2015. Statutory security of supply report. London, UK. Available at: https://www.gov.uk/government/publications/statutory-security-of-supply-report-2015. [Accessed February 1, 2016].

Dodds, P.E. & Demoullin, S., 2013. Conversion of the UK gas system to transport hydrogen. International Journal of Hydrogen Energy, 38(18), pp.7189–7200. Available at: http://www.sciencedirect.com/science/article/pii/S0360319913006800 [Accessed August 27, 2015].

DTI, 2007. The MARKAL Energy Model in the 2007 Energy White Paper, London, UK.

Ekins, P., Anandarajah, G. & Strachan, N., 2011. Towards a low-carbon economy: scenarios and policies for the UK. Climate Policy, 11(2), pp.865–882. Available at: http://dx.doi.org/10.3763/cpol.2010.0126.

Heaton, C., 2014. Modelling Low-Carbon Energy System Designs with the ETI ESME Model., London, UK. Available at: http://www.eti.co.uk/wp-content/uploads/2014/04/ESME_Modelling_Paper.pdf.

Helm, D., 2014. The European framework for energy and climate policies. Energy Policy, 64, pp.29–35. Available at: http://www.sciencedirect.com/science/article/pii/S0301421513004151 [Accessed December 5, 2014].

IEA, 2014. Energy Technology Perspectives 2014: Harnessing Electricity's Potential, Paris, France.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories H. S. Eggleston et al., eds., Japan: IGES. Available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_1_Overview.pdf.

IPCC, 2014. Summary for policymakers. In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pp. 1–31.

Kannan, R. et al., 2007. UK MARKAL model documentation, London, UK. Available at: www.ukerc.ac.uk.

Loulou, R. & Labriet, M., 2007. ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. Computational Management Science, 5(1-2), pp.7–40. Available at: http://www.springerlink.com/index/10.1007/s10287-007-0046-z.

McGlade, C. & Ekins, P., 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 [deg]C. Nature, 517(7533), pp.187–190. Available at: http://dx.doi.org/10.1038/nature14016.

McGlade, C.E. et al., 2014. A bridge to a low carbon future? Modelling the long-term global potential of natural gas, London, UK.

McJeon, H. et al., 2014. Limited impact on decadal-scale climate change from increased use of natural gas. Nature, 514(7523), pp.482–485. Available at: http://dx.doi.org/10.1038/nature13837.

MacKay, D.J.C. and T.J. Stone, Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use. 2013, Department of Energy & Climate Change: London

Moniz, E.J., Jacoby, H.D. & Meggs, A.J.M., 2010. The future of natural gas, Cambridge, Massachusetts: Massachusetts Institute of Technology. Available at: http://web.mit.edu/mitei/research/studies/documents/natural-gas-2011/NaturalGas_Report.pdf.

National Grid, 2015. Future Energy Scenarios, London, UK.

National Grid, 2014. UK Future Energy Scenarios, London, UK.

National Grid, 2013. UK Future Energy Scenarios, London, UK.

National Grid, 2012. UK Future Energy Scenarios, London, UK.

National Grid, 2011. UK Future Energy Scenarios, London, UK.

Pye, S., Sabio, N. & Strachan, N., 2015. An integrated systematic analysis of uncertainties in UK energy transition pathways. Energy Policy, 87, pp.673–684.

Remme, U. et al., 2002. Operations Research Proceedings 2001: Selected Papers of the International Conference on Operations Research (OR 2001) Duisburg, September 3--5, 2001. In P. Chamoni et al., eds. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 59–66. Available at: http://dx.doi.org/10.1007/978-3-642-50282-8_8.

World Energy Council, 2014. World Energy Trilemma Time to get real – the myths and realities of financing energy systems, London, UK.

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