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A Bridge to a Low-Carbon Future? Modelling the Long-Term Global Potential of Natural Gas

Research Report

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Executive Summary

This project uses the global TIMES Integrated Assessment Model in UCL ('TIAM-UCL') to provide robust quantitative insights into the future of natural gas in the energy system and in particular whether or not gas has the potential to act as a 'bridge' to a low-carbon future on both a global and regional basis out to 2050.

We first explore the dynamics of a scenario that disregards any need to cut greenhouse gas (GHG) emissions. Such a scenario results in a large uptake in the production and consumption of all fossil fuels, with coal in particular dominating the electricity system. It is unconventional sources of gas production that account for much of the rise in natural gas production, with shale gas exceeding 1 Tcm after 2040. Gas consumption grows in all sectors apart from the electricity sector, and eventually becomes cost effective both as a marine fuel (as liquefied natural gas) and medium goods vehicles (as compressed natural gas).

We next examine how different gas market structures affect natural gas production, consumption, and trade patterns. For the two different scenarios constructed, one continued current regionalised gas markets, which are characterised by very different prices in different regions with these prices often based on oil indexation, while the other allowed a global gas price to form based on gas supply-demand fundamentals. We find only a small change in overall global gas production levels between these but a major difference in levels of gas trade and so conclude that if gas exporters choose to defend oil indexation in the short term, they may end up destroying their export markets in the longer run. A move towards pricing gas internationally, based on supply-demand dynamics, is thus shown to be crucial if they are to maintain their current levels of exports.

Nevertheless, it is also shown that, regardless of how gas is priced in the future, scenarios leading to a 2 °C temperature rise generally have larger pipeline and LNG exports than scenarios that lead to a higher temperature increase. For pipeline trade, the adoption of any ambitious emissions reduction agreement results in little loss of markets and could (if carbon capture and storage is available) actually lead to a much greater level of exports. For LNG

the significant role that gas can

future coal demand in the emerging economies in Asia, markets that are largely supplied by LNG at present, we demonstrate that

should actively pursue an ambitious global agreement on GHG emissions mitigation if they want to expand their exports. The

have important implications for the negotiating positions of gas exporting coun

going discussions on agreeing an ambitious global agreement on emissions reduction.

The GHG mitigation polices that lead to the largest levels of future natural gas consumption are also examined. We find that up to the

CO_2 tax the greater the level of g

globally; however, by 2050, a CO_2 tax more commensurate with a 3 °C temperature rise leads to the highest level of gas consumption observed in that year in any scenario. This global pattern is not observed in all regions, however, and indeed some countries such as Canada and India display very different behaviour. We further

an important effect of increasing gas consumption, even at low imposed CO_2 tax levels.

Turning to the overall role of gas in a low-carbon future global energy system. In a scenario that provides a 60 per cent chance of limiting the mean surface temperature rise to 2 °C, gas consumption rises until 2035 and indeed is larger than in a case with no GHG emissions reductions on a global level between 2015 and 2035. We therefore conclude that there is a good potential for gas to act as a transition fuel to a low-carbon future up to 2035. However, there are a number of important conditions to this result.

First, the bridging period is strictly time-limited. Global gas consumption declines in all years after 2035 whilst it continues to rise in scenarios leading to higher average temperature rises: any increase in near-term periods must be followed by a subsequent reduction in later periods.

Second, the absolute and relative increase in gas consumption (between the scenario limiting the temperature rise to 2 °C and one with no GHG emissions reductions) must occur alongside a much greater reduction in coal consumption again in both absolute and relative terms. Further, gas is only a short-term complement to the much larger increase in low-carbon energy sources that must occur to replace the reduction in coal consumption and for the low-carbon transition actually to be achieved. Advocacy of gas as a transition fuel therefore needs a convincing narrative as to how global coal consumption can be curtailed and be replaced by low-carbon, non-gas energy sources.

Third, carbon capture and storage (CCS) is of particular importance. In a 2 °C scenario in which CCS is not available, gas consumption peaked in 2025 and declined terminally thereafter: the role that gas can as a transition fuel play was thus substantially reduced.

'PVSUI PVS EFÎOJUJPO PG UIF CSJEHJOH SPMF UIBU gas could play partly relies on to the difference in gas consumption between a 2 °C scenario and a scenario with no GHG emission reduction policies. In this latter scenario there is a reversal of the USFOE UIBU JT DVSSFOUMZ CFJOH FYIJCJUFE JO NBOZ regions away from coal-based power generation and the average surface temperature rise in 2100 is around 4 °C. If we were to compare gas consumption in the 2 °C scenario with a scenario that results in a lower temperature rise, for FYBNQM°E sBenario, then the advantage from a climate perspective conveyed by consuming BEEJUJPOBM HBT JT TJHOJÎDBOUMZ MFTTFOFE

5IF ÎGUI BOE ÎOBM DBWFBU JT UIBU U QBUUFSO JT OPU FYIJCJUFE CZ BMM S to play a bridging role in some regions but not in others. Of the 13 regions studied, gas had limited PS OP QPUFOUJBM UP BDU BT B USBO (Africa, Canada, Central and South America, the .JEEMF &BTU BOE .FYJDP B HPPE QP (Australia, Other Developing Asia, and the United States), and a strong potential in four (China, Europe, India, and Japan and South Korea). Again this is dependent on the availability of CCS, with natural gas only remaining a strong bridge in China if CCS is not available.

'JOBMMZ XF ÎOE UIBU UIFSF JT TJHOJ widespread growth in shale gas production in the future, with little difference in production levels under different long-term emissions mitigation targets. However, this is sensitive to the availability of CCS, to the relative cost assumptions of shale gas compared with other conventional and unconventional sources, and to the levels of fugitive emission that occur during shale gas production. These latter two areas require TJHOJÎDBOU GVSUIFS SFTFBSDI CFGP concluded that shale gas has an important role to play in the transition to a low-carbon global energy system.

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Modelling Approach

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2.1. Overview of TIAM-UCL

The TIMES Integrated Assessment Model in UCL ('TIAM-UCL') is a technology-rich, bottom-up, whole-system model that minimises energy system cost or maximises social welfare as explained further below) under a number of imposed constraints. It models all primary energy sources (oil, gas, coal, nuclear, biomass, and renewables) from resource production, trade, conversion, and sectoral end-use.

TIAM-UCL is based on the ETSAP-TIAM model, a linear programming, partial equilibrium energy system model developed and maintained by the IEA's Energy Technology Systems Analysis Programme ('ETSAP') (Loulou & Labriet 2007). The 16-region TIAM-UCL model, developed under the UK Energy Research Centre (UKERC) Phase II, has broken out the UK from the previous Western Europe region in the 15-region ETSAP-TIAM model to allow more specific analysis of the UK in a global context

The 16 regions in TIAM-UCL are shown in Figure 1, with their names and regional abbreviations presented in Table 1. For clarity, in much of the analysis that follows, we aggregate some of these regions together. The proportions of existing (as of 2011) electricity generation and primary energy supply that are coal, oil, gas, nuclear and renewables within each of the regions are outlined in the appendix

Table 1. List of regions and abbreviations used in this report in the 16 region TIAM-UCL model

Region	Abbreviation
Africa	AFR
Australia and New Zealand	AUS
Canada	CAN
Central and South America	CSA
China	CHI
Eastern Europe	EEU
Former Soviet Union	FSU
India	IND
Japan	JAP
Mexico	MEX
Middle East	MEA
Other Developing Asia	ODA
South Korea	SKO
United Kingdom	UK
United States	USA
Western Europe	WEU

Figure 1. Map of TIAM-UCL regions

TIAM-UCL is a ‘demand-driven’ model. This means that the model must ensure that all energy service demands (such as tonnes of production of iron and steel or billion passenger vehicle kilometres) within all regions are met either by using energy conversion devices and technologies or by reducing service demand. There are a total of 43 energy (depending on whether or not the sources are renewable). These assumptions for natural gas are discussed in more detail in Section 2.3 below. All

In the following scenarios, GHG (i.e. both CO_2 and non-CO_2) emissions are generally constrained on a global level. A further assumption is that GHG emissions permits can be traded between any region in the model from 2020 onwards[1]. This means that there is a truly global effort to reach the required level of emission reduction, with the model always choosing the most cost effective region in which to reduce emissions. Since the model endogenously generates the marginal cost of mitigating CO_2, equivalent to a CO_2 UBY commensurate with a certain level of emissions reduction, in this situation there would be a single, global price of CO_2.

5IJT TJUVBUJPO DPOUSBTUT XJUI FYPHFOPVTMZ JNQPTJOH regional reduction targets and not allowing emissions trading. In this case regions would effectively be acting in competition for low-carbon commodities, there would be regionally different CO_2 QSJDFT SFÏFDUJOH UIF DPTU PS FBTF PG SFBDIJOH the required levels of emissions reduction, and overall energy system costs would be higher[2]. We use the former of these two approaches as we are interested in the most cost effective manner in which to limit the temperature target to 2 °C (or other levels as discussed below).

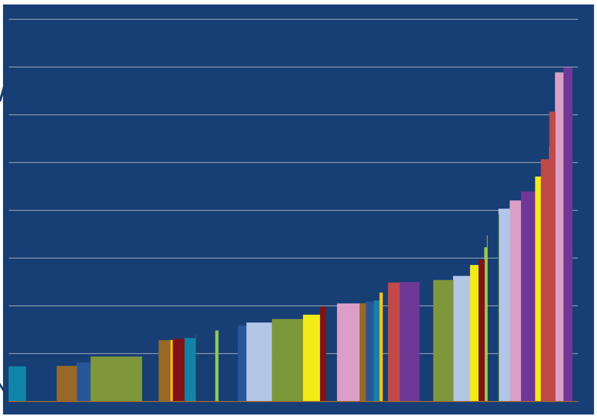
2.3 Mlgasin TIAM-UCL

2.3.1 Gspl

There are a total of eight categories of ‘conventional’ and ‘unconventional’ gas modelle(8.2ferue.70le(8.2feru588 473Dfer)12.1(enuncon)24(v)12(ention (ppr)12on)24(

delfectivel(er)1liff(er)1llet totes th21unconvention 2 geons

In TIAM-UCL, they are modelled through JOUSPEVDJOH NBYJNVN BOOVBM QSPEVDUJPO HSPXUI BOE NBYJNVN AEFDMJOF SBUF SFTUSJDUJPOT 5IFZ BSF imposed on each cost element of each category of gas in each region, and ensure that the production GPMMPXT B NPSF SFBMJTUJD QSPÎMF PW



In each region, production of each cost element of each category of gas can initially increase in BOZ HJWFO ÎWF ZFBS QFSJPE BU B NBYJ 0.5 to 1 per cent of the total resource potential of that element (this is called the 'seed value'). This is subsequently allowed to double every two years. Slower rates of increase are obviously allowed if EFTJSFE CVU UIJT EFTDSJCFT UIF NBYJN which production can grow over time.

%FDMJOF SBUFT BSF EFÎOFE UP CF AIPX SBQJEMZ UIF QSPEVDUJPO GSPN EJGGFSFOU DBUFHPSJFT PG ÎFME JT EFDMJOJOH BOE IPX UIJT NBZ CF FYQFDUFE UP DIBOHF in the future' (Sorrell et al. 2012). The decline rate constraints introduced into TIAM-UCL are slightly NPSF DPNQMFY 8IFO NFBTVSJOH UIF BWFSBHF EFDMJOF SBUF GPS B HSPVQ PG ÎFMET JU JT JNQPSUBOU UP distinguish between: (i) the 'overall' or 'observed' decline rate, (ii) the 'post-peak' decline rate, and (iii) the 'natural decline rate'.

The observed decline is the decline in production TFFO JO BMM DVSSFOUMZ QSPEVDJOH ÎFMET JODMVEJOH those that have yet to pass their peak. The post-peak decline refers to the decline seen just from UIF TVCTFU PG ÎFMET UIBU BSF UIFNTFMWFT JO EFDMJOF Finally, the natural decline is the rate at which QSPEVDUJPO GSPN BOZ ÎFME XPVME EFDMJOF JO UIF absence of any additional capital investment.

The increases in production from new capital investment for a particular resource in a particular region are determined endogenously within TIAM-UCL and so the ‘natural’ decline rate is the most appropriate to use to specify production constraints in TIAM-UCL.

Natural decline rates were generated for each region as described by McGlade (2013) and are TQFDJÎFE BT DPOTUSBJOUT JO 5*". 6$- JO UIF GPSN PG FRVBM NBYJNVN BOOVBM SFEVDUJPOT 5IJT SFTVMUT JO DPNQPVOE EFDMJOF PWFS UJNF 'PS FYBNQMF TBZ UIF decline rate of a given region is 4 per cent. In a ten year period, production can fall to no more than 66 per cent of its initial production (1-0.96 ^{10} = 66 per cent). The model is free to choose to decline at MFTT UIBO UIF TQFDJÎFE SBUF PS UP HSPX QSPEVDUJPO (subject to the growth constraint). It can do so, however, only if the resource remaining after any JODSFBTF JT TVGÎDJFOU UP BMMPX JU UP EFDMJOF BU OP HSFBUFS SBUF UIBO UIF TQFDJÎFE NBYJNVN JO FBDI subsequent year over the remaining time horizon. These growth and decline constraints are imposed on each resource element of each category of gas within each region.

Estimates of shale gas decline rates are currently a source of controversy, with some commentators suggesting that future decline rates have been underestimated, i.e. that production from shale gas wells is declining at a faster rate than assumed by many analysts (Berman & Pittinger #FSNBO "O FYUFOEFE EJTDVTTJPO PG this issue is provided in McGlade et al. (2013a), but it is nevertheless generally accepted that production from shale gas wells (and the other two unconventional sources) declines at a much GBTUFS SBUF UIBO DPOWFOUJPOBM XFMMT 'PS FYBNQMF within one year production from shale gas wells can decline by around 50 per cent from the levels TFFO JO UIF ÎSTU NPOUI PS TP XIJMF EFDMJOF SBUFT for conventional sources tend be closer to around 5 per cent every year (IEA 2009). For the modelling of the depletion rate constraints within TIAM-UCL, we therefore assume different decline rates between conventional and unconventional gas.

2.4 GasTd

5IF HBT USBEF NPEVMF PG 5*". 6$- TQ
UIF DPTUT FGÎDJFODJFT BTTPDJBUF
constraints of the trading of gas by both pipeline BOE MJRVFÎFE OBUVSBM HBT -/(5IJ
substantially revised as part of this project. This section contains the assumptions and sources CFIJOE UIFTF NPEJÎDBUJPOT UIFTF I
JO DPOKVODUJPO XJUI BOE UP SFÏFD
the UK Energy Research Centre project on Global Gas Security (see .wwkp RF3LGSa)

2.4.1 Pp

1JQFMJOF USBEF JT OPU B QFSGFDUM
mechanism and gas is lost while it is being transported by two mechanisms. First, compressor stations are located at various intervals along a QJQFMJOF UP NBJOUBJO QSFTTVSF UP
IPX PG HBT

5IFTF GPS FYBNQMF SFEVDF TVSGBD
UIF JOTJEF PG UIF QJQF PS BMMPX U
uphill. Compressor stations require elect004A00CE1004A03460

Estimates for inter regional transport figures are slightly more complex however The first step is to estimate the percentage of gas lost per km per unit volume flowing through large scale pipelines This can then be converted into a total percentage loss by multiplying it by assumed lengths of pipelines between regions (also set out below).

This first step focuses on compressor stations

The EIA (2007) provides data on the electricity requirements of compressor stations on eleven transmission pipelines within the United States. These data, and how they are manipulated, are summarised in Table 2. To summarise, each compressor is estimated to require 0.56 MW electricity per million cubic metres mcm flowing through each day. By assuming that there is one compressor station every 150 km (NETL 2012), and an electrical conversion efficiency of per cent (from the IEA 2006)[4], it can be estimated that around $^{-5}$ per cent of gas entering a pipeline is lost for every kilometre it travels. As mentioned above this is emitted as CO_2, and is converted at 2.1 $ktCO_2$ per mcm gas consumed.

Regarding gas lost as CH_4, NETL (2012) indicates that based on EPA emission data from 2003 in the USA, the volume lost both from operations at compressor stations and as the g

pipelines i e through accidenta $^{-6}$ per cent/km of pipeline. Gas lost in this way results in 678 tCH_4 per mcm gas vented. Taken together, a total of ^{5} per cent of gas entering a pipeline is therefore lost for every km it travels.

The next stage is to estimate the

constructing and operating new pipelines. Cobanli (2014) provides length, capacity, and cost estimates for a number of pipelines, which are set out in Table 3. To this we have added the recent Nord Stream pipeline (Chyong et al. 2010). Trade process costs in TIAM-UCL are calculated per unit of gas transported, and we convert our estimate to an average cost per km and per unit of gas, giving mcm km in Operat

are simply assumed to be 2 per cent of the capital investment per year (Core Energy Group 2012), with each pipeline assumed to have a lifetime of 40 years.

---

[4] We have taken the average compressor efficiency from OE
transmission pipelines regardless of start and end region. This relies upon the assumption that both existing and new long range transmission pipelines w
stations rather than take the current average efficienc

5P QSPWJEF BO FYBNQMF DPOTJEFS B LN QJQFMJOF transporting 30 Bcm/year. The above assumptions input to TIAM-UCL would be that capital costs are CJMMJPO BOE UIF PQFSBUJOH DPTUT NJMMJPO year. A total of 5.6 per cent of the gas transported (1.7 billion cubic metres (Bcm)) would be lost every year. Of this, 1.4 Bcm would be combusted and result in 2,900 ktCO_2 and the remainder (0.3 Bcm) would be vented, resulting in 220 ktCH_4. Total GHG emissions would therefore be around 8.5 MtCO_2e.

5IF OFYU TUBHF JT UP FTUJNBUF WJBCMF QJQFMJOF SPVUFT between different regions and reasonable distances for these. These are shown in Table 4 for each of the 16 regions given previously in Table 1; if there is no entry in a row or column then pipeline trade is not possible between these regions.

" ÎOBM WBSJBCMF UIBU OFFET UP CF FTUJNBUFE for pipeline trade is any constraints on the construction of new pipelines. The most transparent manner in which to impose such B DPOTUSBJOU JT UP FYBNJOF IJTUPSJDBM SBUFT PG increase in trade between regions and use this to TFU B NBYJNVN MJNJU PO UIF SBUF BU XIJDI OFX pipelines can be constructed. Figure 5 thus shows the increases in inter-regional pipeline trade over UIF QBTU ZFBST XJUI OFHBUJWF ÎHVSFT JOEJDBUJOH JNQPSUT BOE QPTJUJWF ÎHVSFT FYQPSUT /PUF UIBU UIJT is not net trade, rather the total volumes either FOUFSJOH PS FYJUJOH FBDI PG UIF SFHJPOT CZ QJQFMJOF Build-rate constraints within TIAM-UCL can be @`ðP`F T BM S, rather L004F00450003reases in inter-JAd30042004F>6 interaints oi6D00030053>30043>sai0460003

Scenarios Constructed

3

This section describes the key assumptions within scenarios implemented in this project to investigate the questions posed in Section 1.1.

As discussed in Section 2.1, the base year of TIAM-UCL is 2005. For the scenarios that require some level of GHG emissions reduction, the model is therefore free to take actions to reduce GHG emissions from 2005 onwards. However, despite the Kyoto protocol and other political commitments to reduce emissions, observed global GHG emissions between 2005 and present have not been following the trajectory generally produced in mitigation scenarios. It is thus somewhat unreasonable to allow the model to do this. In contrast, the results from scenarios run that require no GHG abatement actually match observed investment patterns and GHG emissions quite closely.

To prevent mitigation that has not been observed in reality, the results (infrastructure investments,

Therefore, unless otherwise noted, these scenarios do not impose the cost markups used in the REGIONALGP scenario and so they carry the assumption that there is a move towards a global gas price.

3.3 N[illegible]

5IF UIJSE BOE ÎOBM BSFB PG JOUFSFTU SFHBSET UIF role that natural gas can play in a low-carbon energy system. To investigate this, we run discrete scenarios that result in certain levels of average HMPCBM UFNQFSBUVSF SJTF 5IF EFÎOJUJPO VTFE IFSF for a 'low-carbon' future is an emissions pathway that is consistent with keeping the global average surface temperature rise below 2 ºC in all years: the level agreed on by makers that should not FYDFFEFE 6/'$$$ 6/'$$$ "T discussed in the previous section, since the climate module of TIAM-UCL is calibrated to the MAGICC model, there will be around a 60 per cent chance of keeping the temperature rise to this level.

8F BSF BMTP JOUFSFTUFE JO FYBNJOJ do not mitigate the temperature rise to this level. This is partly because the IEA (2011) suggests that its 'golden age of gas' scenario, a scenario that modelled a large increase in gas consumption, will lead to a 3.6 ºC average surface temperature rise, and partly to allow us to investigate changes in gas's role in when the temperature change FYDFFET ºC UIF threshold. We therefore also model emissions pathways that lead to long-term temperature rises of 3 ºC and 5 ºC. 'Long term' is taken here to mean the temperature rise in 2200, and we constrain the model to ensure that these UFNQFSBUVSF UBSHFUT BSF OPU FYD time period i.e. no 'overshoot' of temperature is permitted within the modelling period.

There are a wide variety of emissions pathways consistent with these temperature rises. The focus IFSF JT OPU TQFDJÎDBMMZ PO FNJTTJ however, and so we have chosen discrete scenarios with the assumptions set out in Table 8. For the emissions-mitigation scenarios (those that limit

Table 8. Description of assumptions for the discrete emissions reduction scenarios

Scenario Name	Description
REF	

the temperature rise to 3 °C and 2 °C), we assume that there are only relatively modest efforts to MJNJU FNJTTJPOT JO FBSMZ QFSJPET BT FYQMBJOFE "T with the scenarios in the previous section, these scenarios assume a move towards a global gas QSJDF VOMFTT TQFDJÎFE PUIFSXJTF

A key assumption in TIAM-UCL is the availability of carbon capture and storage (CCS). It has been suggested, and is plausible, that the deployment PG $$4 XJMM QFSNJU XJEFS FYQMPJUBUJPO PG GPTTJM GVFM resource base (IEA 2013b), and so it is likely to have a major impact on the levels of gas produced and consumed. Nevertheless, whether CCS will actually be commercialised or not is currently far from certain (Watson et al. 2012). For the 2DS scenario, we therefore run two separate scenarios, one which permits the widespread deployment of CCS, and the other which assumes that CCS is not available JO BOZ UJNF QFSJPE 5IF TVGÎY @OP$$4 JT BEEFE when it is assumed that CCS is not available.

*O TDFOBSJPT UIBU QFSNJU $$4 JU DBO ÎSTU CF BQQMJFE to electricity and industrial technologies from 2025. Assumptions are purposely optimistic on the rate at which it can be deployed: in 2025 in each region $$4 DBO CF BQQMJFE UP B NBYJNVN PG QFS DFOU PG total electricity generation while in the industrial sector it can capture between 10-20 per cent of process emissions and emissions from generating process heat (depending on the technology and TQFDJÎD TFDUPST "GUFS BMM $$4 UFDIOPMPHJFT DBO HSPX BU B NBYJNVN SBUF PG CFUXFFO QFS DFOU QFS BOOVN 4PNF NBYJNVN MFWFMT PG CCS penetration are, however, applied in certain TFDUPST 'PS FYBNQMF B NBYJNVN PG QFS DFOU of emissions can be captured from process heat technologies in the iron and steel industries in each region. CCS is assumed to have a 90 per cent capture rate.

3.3.1 C[illegible]

[illegible]

#FGPSF MPPLJOH BU SFTVMUT JU JT XPSUI FYQMPSJOH here what is actually meant by the phrase a gas ‘bridge’ or natural gas ‘acting as a transition fuel’ as introduced in Section 1 becauereebs trP G,ÒE p ð VN SM0Ò``A¬è%P`0@0P ``ð

The second is a relative increase in consumption, over some period, in a GHG mitigation scenario compared with consumption in a non-mitigation scenario. There is also disagreement over the level of emissions reduction in the GHG mitigation TDFOBSJP UIBU TIPVME CF TQFDJÎFE GPS UIJT UP RVBMJGZ as a ‘low-carbon scenario’.

However, since the 2 º$ MJNJU XBT FYQMJDJUMZ JODMVEFE in the Copenhagen Accord of 2009 (UNFCCC BOE JT TUJMM JODMVEFE JO UIF UFYU BEPQUFE CZ the UNFCCC in Durban (UNFCCC 2012), we use a scenario with emissions commensurate with a 2 °C temperature rise as our principal GHG mitigation scenario.

In this report we will therefore make reference to gas acting as a transition or bridging fuel in scenarios that satisfy this 2 °C temperature rise limit in both a relative and absolute sense. It is worth clarifying precisely what is meant by these roles, and the scenarios with which these roles are being compared, since this is something that otherwise can lead to some confusion (Strachan 2011).

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 than in 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.

Gas Price Development

4

Figure 9 displays the consequent growth in GHG emissions globally. From around 45 Gt CO_2-eq in 2010, GHG emissions rise at an average of 1 per cent/year to over 65 Gt CO_2-eq in 2050. China accounts for over 20 per cent of this rise, but annual emissions in India, Africa and the Middle East all grow by around 2.5 Gt CO_2-eq. Nevertheless, per capita emissions remain far higher in developed regions, with levels in Canada HJWFO UIF FYUFOU PG VODPOWFOUJPOBM PJM QSPEVDUJPO by far the highest (30 tCO_2/capita in 2050).

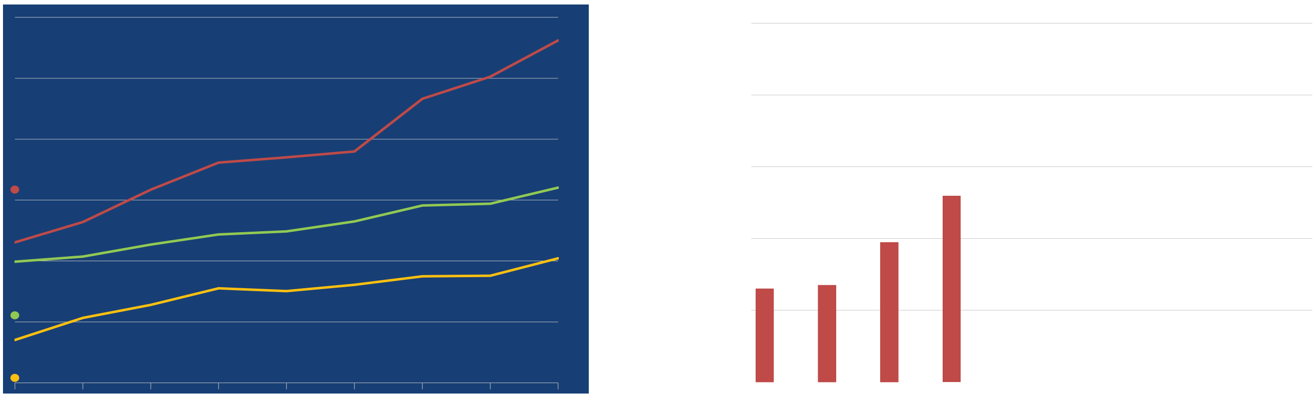
Figure 10 shows gas production by type and region. Total gas production doubles by 2050, with the unconventional sources of gas (shale gas, tight gas and coal bed methane) accounting for most of this growth. Of these, shale gas rises to the largest EFHSFF BOE BOOVBM QSPEVDUJPO FYDFFET USJMMJPO cubic metres (Tcm) from 2040 onwards. Similar to the present situation, there remains a diverse NJY JO QSPEVDUJPO HFPHSBQIJDBMMZ BOE OP TJOHMF region accounts for more than 25 per cent global production in any period. China has the largest growth in relative terms (more than tripling by 2050), but the Middle East grows most in absolute terms (by over 0.8 Tcm annually). Production by

We showed previously in Figure 4 how we model the availability and production costs of shale gas

5IFSF JT BMTP B SFEVDUJPO JO -/(FYQPSUT GSPN "GSJDBO DPVOUSJFT XJUI BMM PG UIFJS FYQPSUT UP Europe displaced by pipeline trade (both from Africa and FSU). Overall, the FSU continues to EPNJOBUF QJQFMJOF USBEF XIJDI HSPXT FYQPSUT UP &VSPQF CVU NPSF TJHOJÎDBOUMZ BMTP JODSFBTFT JUT FYQPSUT UP $IJOB UP #DN ZFBS CZ &YQPSUT CZ QJQFMJOF BMTP SJTF GSPN UIF .JEEMF &BTU principally to India but also in later periods to ODA.

The right-hand side of Figure 14 shows internally-generated gas prices from representative regions JO FBDI PG UIF UISFF NBJO CBTJOT JEFOUJÎFE JO Section 3.1, with the price differences from the

Figure 15. Gas prices in REF_REGIONALGP and differences in gas price from REF_GLOBALGP



4.2 Ef

This section primarily discusses the differences between the scenario that assumes a continuation of the current situation in gas markets (REF_REGIONALGP) and the scenario described above that assumes a move towards a global gas price. 'JHVSF ÎSTU QSFTFOUT UIF HBT QSJDFT JO 3&'@ REGIONALGP in the three different regional basins. There is a continuation of large cost differentials between the regions, and the price in Japan grows UP PWFS (+ m B OFBST EPVCMJOH PWFS UIF NPEFM – horizon. Again these prices generated do not match the actual prices in 2010, nevertheless, as above, the ordering of prices generated in TIAM-UCL is correct in 2010, with the United States DIFBQFTU BOE +BQBO NPTU FYQFOTJWF 5IF cost differential between the USA and Europe is BMTP BQQSPYJNBUFMZ DPSSFDU *U JT that the regional differences in price between REF_REGIONALGP and REF_GLOBALGP are not as large as the imposed cost mark-ups that were shown in 5BCMF (+ UP &VSPQF BOE (+ UP +BQBO

This occurs both because there is a higher level of gas consumption in all regions in the European and Asian basins when there is a move towards a (lower) global gas price in REF_GLOBALGP, and because they also produce less gas domestically. 5IJT JT TIPXO JO 'JHVSF XJUI QPTJUJWF ÎHVSFT meaning that consumption or production is greater JO 3&'@(-0#"-(1 'PS FYBNQMF JO UIF production in China is around 100 Bcm lower and it consumes around 80 Bcm more gas in REF_GLOBALGP than in REF_REGIONALGP. Similarly, throughout the 2030's production in Europe is around 100 Bcm lower in REF_GLOBALGP while consumption is over 50 Bcm greater.

$POWFSTFMZ UIF FYQPSUJOH SFHJPO considerably more gas in REF_GLOBALGP and noticeably reduce domestic consumption. For FYBNQMF QSPEVDUJPO CZ UIF 'PSNFS (FSU) region in the 2030's is around 250 Bcm greater in REF_GLOBALGP, while consumption is an average of 150 Bcm, or around 15 per cent, lower. It is worth noting, however, that consumption in FSU in both scenarios grows in absolute terms from current levels (by 35 per cent in REF_GLOBALGP and over 70 per cent in REF_REGIONALGP in 2050); in reality this may be mitigated by the considerable FGÎDJFODZ TBWJOHT UIBU BSF UIPVHI but the model does not take these into account.

Despite these changes at the regional level, there is not a major difference on aggregate global production or consumption levels. The net change shown in Figure 16 remains less than 250 Bcm globally in all periods, less than 4 per cent total consumption in REF_GLOBALGP. As a result, the main change between a move towards a global gas price and a continuation of regional gas pricing scenario is the level of gas that is traded. This is demonstrated in Figure 17, which displays the QFSDFOUBHF PG EPNFTUJD QSPEVDUJ (by both by pipeline and LNG) from the three major FYQPSUFS SFHJPOT "VTUSBMJB UIF Union, and the Middle East).

*O 3&'@3&(*0/"-(1 UIF MFWFM PG FYQ UISFF SFHJPOT GBMMT ESBNBUJDBMM in particular fall to negligible levels by 2040, but FYQPSUT GSPN .&" BOE "64 BMTP GBM levels to 10 per cent and 25 per cent respectively. 5IFTF DIBOHFT SFÏFDU UIF IJHIFS QSJ therefore the reduced consumption and increased production in the importing regions.

In stark contrast, in REF_GLOBALGP Australia DPOTJTUFOUMZ FYQPSUT BSPVOE QFS DFOU PG JUT production to other regions over the model horizon, up from around 50 per cent currently), XIJMF '46 BOE .&" FYQPSU CFUXFFO BSPVOE QFS DFOU BMUIPVHI UIF BCTPMVUF MFWFM PG FYQPSUT JT of course higher in these two regions).

These results therefore suggest that a move towards a global gas price based on supply-demand dynamics, and a move away from oil QSJDF JOEFYBUJPO JT UIF TUSBUFHZ UIBU HBT FYQPSUJOH regions should follow if they want to increase, PS FWFO NBJOUBJO UIFJS DVSSFOU MFWFMT PG FYQPSUT Further dynamics in changes to volumes of gas traded, looking at the relative importance of market structure and GHG mitigation, and distinguishing between LNG and pipeline trade, are discussed in more detail in Section 5.3.

4.3 Syfh

5IJT TFDUJPO BJNFE UP FYQMPSF NB market dynamics in TIAM-UCL in a scenario that disregards any need to cut GHG emissions. There is large uptaay from oil

We also modelled two different scenarios for future gas markets. One continued current regionalised gas markets, which are characterised by very different prices in different regions with these QSJDFT PGUFO CBTFE PO PJM JOEFYBUJPO XIJMF UIF other allowed a global gas price to form based on gas supply-demand fundamentals. We found only a small change in overall global gas production levels between these but a major difference in levels of gas trade. We concluded that if gas FYQPSUFST DIPPTF UP EFGFOE PJM JOEFYBUJPO JO UIF TIPSU UFSN UIFZ NBZ FOE VQ EFTUSPZJOH FYQPSU markets in longer term: a move towards pricing gas internationally, based on supply-demand dynamics, was thus shown to be critical if they are UP NBJOUBJO UIFJS DVSSFOU MFWFMT PG FYQPSUT

The Variation of Gas Consumption with GHG Mitigation

5

We saw in the previous section that gas production doubles by 2050 when there is no constraint on GHG emissions. There was also a major increase in the level of coal production. It is therefore possible that, when a GHG emission constraint is applied, providing an incentive to move away from carbon-intensive coal in the electricity and other sectors, there may be an even greater uptake of gas. On the other hand, given that GHG emissions also inevitably result from the consumption of gas, a strong move towards mitigating GHG emissions could force gas out of the system. This section investigates the effect on gas consumption of different emission mitigation policies, focusing on those policies that lead to the largest uptake of gas in the future[8]. As discussed in Section 3.2, one PG UIF TJNQMFTU XBZT PG FYQMPSJOH UIFTF EZOBNJDT is by introducing a wide range of CO_2

In 2030 gas continues to be used to produce a

"MM PUIFS NJMFTUPOF ZFBST FYIJCJU B QFBL BU TPNF level of CO_2 UBY BT TIPXO 'PS FYBNQMF JO it is clear that there is a distinct peak in gas consumption at a CO_2 UBY BU $_2$. Figure 20 shows that a low CO_2 UBY MFBET UP IJHIFS NBYJNVN levels of gas consumption in later periods, while increasing the CO_2 UBY DBVTFT UIF FNJTTJPOT JO different periods to converge to a range of 4-5 Tcm/year, with the 2050 emissions falling fastest and furthest as the CO_2 UBY JODSFBTFT

An alternative manner in which to observe this is HJWFO JO 'JHVSF 5IJT ÎHVSF$_2$ UBY TIPXT UIF $0 MFWFM PO UIF Z BYJT UIBU SFTVMUT JO UIF IJHIFTU MFWFM PG HBT DPOTVNQUJPO JO FBDI ZFBS PO UIF Y BYJT alongside the CO_2 UBYFT HFOFSBUFE and JO UIF 3º$ TDFOBSJPT *O PUIFS XPSET UIF ANBYJNBM HMPCBM gas consumption' line in Figure 21 plots the CO_2 UBY SBUF PG UIF QFBL JO FBDI PG UIF MJOFT TIPXO JO Figure 20 against the year in which it occurs.

Again, it can be seen that while a high CO_2 UBY leads to higher gas consumption in near periods, in later periods the highest gas consumption arises with a lower CO_2 UBY 'SÀ 0000<Z ê€ 0 € 02

At the higher CO$_2$ UBY MFWFMT J F UIPTF UIBU QSPWJEF the emissions reductions more commensurate with a 2 °C temperature rise, when CCS is not available gas is itself displaced from the electricity sector. The emissions from un-abated generation, and the associated cost penalty, mean that gas use in the electricity quickly ceases to be cost effective; the model instead relies on biomass and renewables.

In summary, Figure 22 suggests that CCS is generally very important in leading to a higher level of gas consumption in the future. This is particularly the case if the agreed temperature SJTFT BSF OPU UP CF FYDFFEFE 5IF SPMF PG $$4 JT discussed in more detail in Section 6.

5.2 Rlg

Results have so far focussed on the global level; however there are many important underlying dynamics within different regions. This is shown in Table 9. Following a similar process to Figure 21, Table 9 provides the CO$_2$ UBYFT UIBU MFBE UP UIF highest levels of gas consumption within each of the regions indicated. Whilst it can be seen that some regions, such as the United States and Europe, generally follow the global pattern, others, TVDI BT $BOBEB FYIJCJU WFSZ EJGGFSFOU CFIBWJPVS

In Canada, gas consumption is highest when there are never any CO$_2$ UBYFT JNQPTFE 5IJT JT CFDBVTF in any scenario with a CO$_2$ UBY UIFSF JT B SFEVDUJPO in the demand for Canadian unconventional oil.

The production of natural bitumen requires a large amount of heat. This is generally provided by natural gas, and so if there is less demand for this type of oil, there will be less demand for gas.

In contrast in India, it can be seen that the CO$_2$ UBYFT UIBU SFTVMU JO UIF IJHIFTU M consumption are similar to those that are seen in the 2 °$ TDFOBSJP 5IJT TVHHFTUT UIBU HBT DPOTVNQUJPO JO *OEJB JT BMTP from a CO$_2$ emissions reduction perspective CFDBVTF BT XJMM CF TFFO JO UIF O gas consumption substitutes in large part for the DPOTVNQUJPO PG DPBM 5IFTF EZOBN in more detail in the following section, but it is evident that CO$_2$ UBYFT DBO IBWF WFSZ EJG Effects on different regions, and all do not follow 0420045004201

With the REGIONALGP scenarios, pipeline trade in

The Role of Gas in a Low-Carbon Energy System

6

5IJT ÎOBM SFTVMUT TFDUJPO OPX GP on the role of gas in a 2°C future, particularly its role as a ‘bridge’ or ‘transition’ fuel[10]. As mentioned previously, a ‘relative’ bridge is taken to be the period over which consumption is higher in a 2°C scenario than in a case with no emissions reduction policies (our reference case). An ‘absolute’ bridge is taken more simply to be the time when global or regional consumption rises from current levels in a 2°C scenario.

6.1 Gl

Gas consumption in the reference case (REF) was shown previously in Figure 10, but to show more clearly the changes in consumption within each region this is given numerically in Table 10. We have highlighted the year in which consumption in any region reaches a peak and subsequently enters a terminal decline.

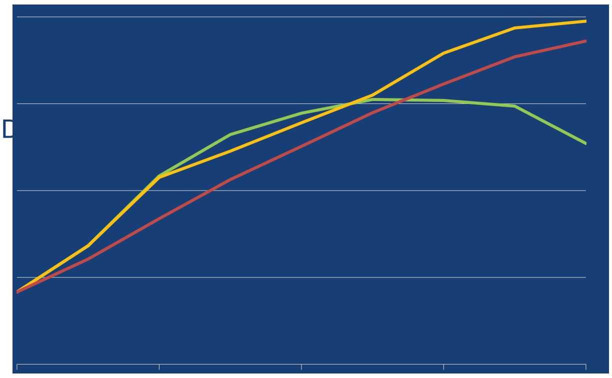
'JHVSF OFYU QSFTFOUT PWFSBMM global level in REF, and the 2°C (2DS) and 3°C (3DS) scenarios, which rely on the emissions reduction assumptions set out previously in Table 8. Figure 24 also provides the percentage changes between these scenarios.

Similar to REF, gas consumption in 3DS grows steadily over the model horizon. However, consumption is on average around 300 Bcm or 7 per cent greater in all years in 3DS relative to REF, although with a slightly larger difference in earlier periods.

In contrast in 2DS total consumption peaks in 2035 at just over 5 Tcm before subsequently declining. 5IF NBYJNVN EJGGFSFODF JO DPOTVN 2DS and REF is just over 500 Bcm (between 2020 and 2025), or nearly 15 per cent greater than consumption levels in REF. With consumption continuing to climb in REF, this difference reduces over time so that by 2040 consumption is lower in %4 *O UIF ÎOBM QFSJPE UIFSF JT B ESPQ BOE DPOTVNQUJPO JO %4 ÎOJT below that in REF.

The sectoral breakdown of consumption in 2DS is given in Figure 25. Figure 25 also displays the differences in consumption in each sector compared with REF (shown previously in Figure 12). As discussed in Section 4.1, consumption in REF was seen to grow in all sectors other than the electricity sector. In 2DS (the LHS of Figure 25) consumption in the electricity sector grows out to 2025 before declining (although still remaining above the consumption levels in REF), while the commercial and residential sectors decline from 2030 onwards. The declines in these three sectors as well as the plateauing of growth in the industrial sector account for the peak and subsequent decline in total consumption in 2DS. Consumption in 2DS is greater than REF in the electricity and industrial sectors in all years, hcm (between 202is green 2Cn in 2DS is e3 TD [(is e3lty and i also ditfmn 2DS)]TJ 0 -1.3 Tconsumptnt

The behaviour seen in Figure 24 and 25 shows a key result: on a global level, gas can play an important role as a bridging fuel both in relative and absolute terms up to 2035. However, there are a number of important caveats to this, upon which this result is very dependent. Global consumption PG DPBM NVTU CF TJHOJÎDBOUMZ SFEVD current levels and relative to the levels seen in REF in all time periods in a 2 ºC scenario. This can be seen in Figure 26, which presents primary energy consumption over time in 2DS, and the changes relative to the REF (shown previously in Figure 8). The line in the lower panel of Figure 26 shows the percentage increase in gas consumption relative to the drop in coal consumption (both in terms of &+ " ÎHVSF PG QFS DFOU NFBOT UIBU UIF ESPQ JO coal consumption is entirely met by an equivalent increase in gas consumption, while 0 per cent means that gas does not contribute at all. It is immediately evident that in both absolute and relative terms coal consumption falls to a much HSFBUFS FYUFOU UIBO HBT JODSFBTFT



Gas offsets three quarters of the drop in coal consumption in 2015. It is clear, however, that at this time the reduction in coal consumption is quite small compared with the major drop seen in subsequent periods. The offsetting role of gas falls rapidly: even though gas consumption is nearly 15 per cent greater in 2DS than in REF in 2020 and 2025 (as shown in Figure 24) this only respectively offsets 30 per cent and 20 per cent of the much greater reduction in coal consumption. Subsequently, as the increase in gas consumption in 2DS relative to REF begins to fall, gas’s contribution decreases even lower.

Eventually after 2035, when both gas and coal consumption are lower than in REF, gas obviously does not offset anything.

However, absolute consumption in 2DS_noCCS peaks in 2025 at just over 4.5 Tcm, and then subsequently declines at an average of 2.3 per cent/year. Therefore by 2030, gas consumption falls below REF and thereafter consumption is significantly lower in all time periods Indeed by 2050 it is over 50 per cent lower. The absence of CCS thus shortens the natural gas bridge in both absolute and relative terms by ten years, and also results in the subsequent need for a very rapid decline in consumption following this bridge. The commercialisation of CCS is therefore crucial for the future role of natural gas in a decarbonised energy system.

A fourth factor to bear in mind is that the definition of the ‘relative bridge given in Section 3.3.1 referred to the difference between a 2 °C scenario and a scenario with no GHG emission reduction policies. It is not necessarily the case, however, that this is the most appropriate comparative scenario For example given the commitments pledged as part of the Copenhagen Accord (UNFCCC 2009), it is unlikely that we are currently proceeding along a ‘no policies’ or ‘reference’ emissions pathway. Similarly a number of air quality and fuel e have been introduced internationally (see e.g. European Parliament & Council of the European Union which may not have the intention of mitigating GHG emissions, but are still likely to result in some emissions reduction, and importantly coal consumption. It could therefore be argued that alterative scenarios such as the IEA’s ‘Current Policies’ or ‘New Policies’ scenarios provide a more appropriate comparison (IEA 2013c).

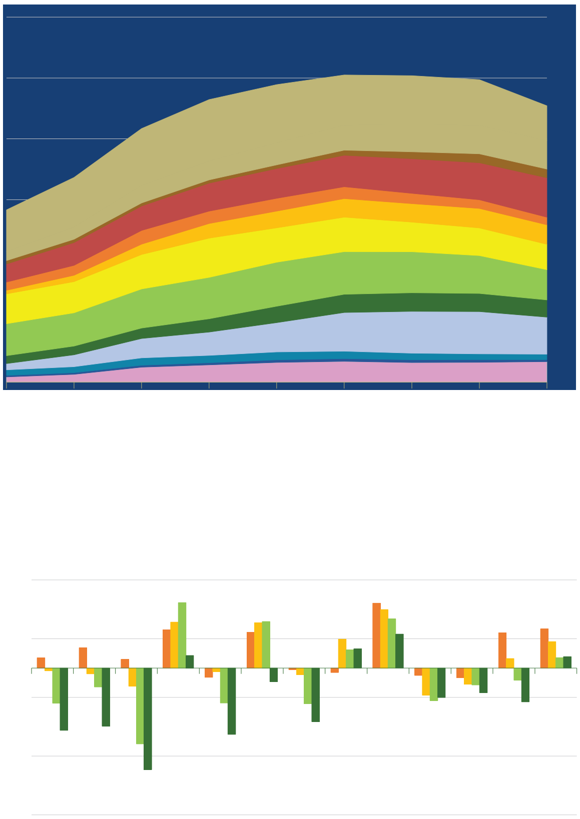
We chose to use a ‘no policies’ scenario to be most explicit about the relevant assu as was discussed in Section 4, coal production is extremely prevalent in this sce some regions that are currently trending away from coal-based electricity generation construct a number of new coal power plants. This could be considered unrealistic. If so, it may be the case that the 3 °C scenario is a better scenario with which to compare gas consumption in the 2 °C scenario. As noted in Section DS results i lower level of coal consumption than in REF.

Consumption in 3DS was shown in Figure 24. While gas still acts as a ‘relative’ bridge in 2DS when compared to 3DS, this is to a much lesser degree The maximum difference be two scenarios is lower (4 per cent in 2025), and indeed after 2030 consumption in 2DS is lower than in 3DS. Further, there is no increase in gas consumption above 3DS until 2020. The ‘relative’ bridge formed by natural gas is thus shortened to 10 years (between 2020 and 2030) and the advantage (from a climate perspective) conveyed by consuming additional gas is s diminished.

6.2 R[illegible]

The final caveat in understanding

Fig29. Absolute gas consumption by region in 2DS, and changes between 2DS and REF



On the other hand, gas consumption in Central and South America (CSA), the Middle East (MEA), BOE .FYJDP .&9 JT MPXFS JO BMM QFSJPET JO %4 Consumption is reduced in all three of these in a number of sectors (electricity, upstream, and residential), but interestingly the largest change occurs in the transport sector, with hydrogen being preferred over CNG in medium goods vehicles.

Table 11 accompanies Figure 29, and provides BDUVBM DPOTVNQUJPO ÎHVSFT XIJMF BMTP IJHIMJHIUJOH the year in which consumption peaks and subsequently declines terminally within any region (if this occurs). The peak in consumption in the USA moves forward by 10 years (from 2035 in REF), and peaks appear in a number of regions that did OPU FYIJCJU POF QSFWJPVTMZ

As with the global-level results, the failure of CCS UP CFDPNF BWBJMBCMF BMTP IBT B TJHOJÎDBOU FGGFDU PO regional consumption levels. This is demonstrated in Figure 30, which, similar to Figure 29, presents absolute production split by region in 2DS_noCCS, and the changes compared to REF. In 2020, a number of regions (particularly Australia and China) increase consumption by an even greater than when CCS was available. However, by 2040 only China has gas consumption greater than in REF. All other regions have reduced consumption, in many cases by quite a substantial degree.

Table 12 again numerically presents the absolute QSPEVDUJPO ÎHVSFT BOE IJHIMJHIUT production years within each region if this occurs. While consumption still does not peak in all regions, in general the peaks occur earlier in this scenario than either REF or 2DS (with CCS). 5IF QFBL GPS UIF 6OJUFE 4UBUFT GP moves further forward to 2020, and European gas consumption peaks in 2025 rather than 2030 in the 2°C scenario when CCS was available.

Tb11. Absolute gas consumption by region in 2 °C scenario including dates when regional DPOTVNQUJPO QFBLT IJHIMJHIUFE DFMMT BMM ÎHVSFT JO #D

Region	2010	2015	2020	2025	2030	2035	2040	2045	2050
AFR	86	129	246	284	324	342	322	326	337
AUS	24	27	31	35	43	45	45	44	33
					▨				
								▨	
							▨		
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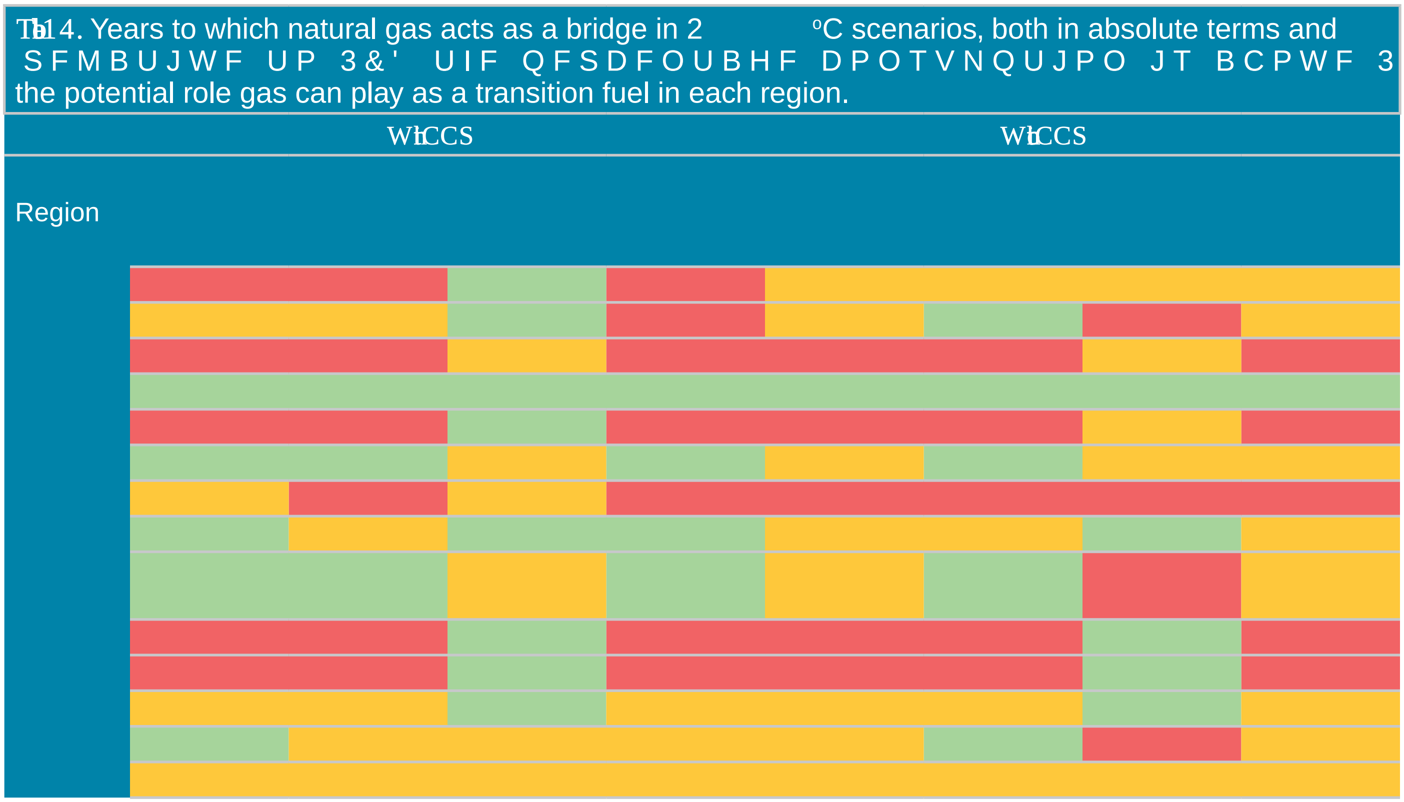
Insights can now be drawn on the role of natural gas as a transition fuel in the 2 °C scenarios in each region. These are summarised in Table 14. This table indicates the latest year to which gas acts as a relative bridge (since in all case the bridging period commences in 2010), the latest year to which gas acts as an absolute bridge, and the percentage by which consumption is greater when the difference between consumption in the 2º$ TDFOBSJP BOE 3&' JT BU JUT NBYJNVN WBMVF

Tb13. Criteria by which duration & magnitude of natural gas bridge in each region is judged

Criteria	Dip	Sn	CinTb6.5
Duration of absolute bridge	Lasts until 2040 or later	2	Green
	Lasts until between 2020 and 2040	1	Orange
	Lasts only up to and including 2020	0	Red
Duration of relative bridge	Lasts until 2040 or later	2	Green
	Lasts until between 2020 and 2040	1	Orange
	Lasts only up to and including 2020	0	Red
.BYJNVN SFMBUJWF JODSF	Greater than 30 per cent	2	Green
	Between 10 per cent and 30 per cent	1	Orange
	Less than 10 per cent	0	Red

Criteria	Sn	Dpfpfb6 hg	Nin Tb6.5	Cin Tb6.5
Strength of bridge	5-6	&YUFOEFE BOE TUSPOH QPUFOUJBM SPMF to act as a transition fuel	Strong	Green
	3-4	More diminished but still maintains a good potential to act as a transition fuel	Good	Orange
	<2	Very limited or no potential role to act as a transition fuel	Limited	Red

Tb14. Years to which natural gas acts as a bridge in 2 °C scenarios, both in absolute terms and SFMBUJWF UP 3&' UIF QFSDFOUBHF DPOTVNQUJPO JT BCPWF 3 the potential role gas can play as a transition fuel in each region.



Region	WiCCS				WiCCS			
	🟥	🟥	🟩	🟥	🟧	🟧	🟧	🟧
	🟧	🟧	🟩	🟥	🟧	🟩	🟥	🟧
	🟥	🟥	🟧	🟥	🟥	🟥	🟧	🟥
	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	🟥	🟥	🟩	🟥	🟥	🟥	🟧	🟥
	🟩	🟩	🟧	🟩	🟧	🟩	🟧	🟧
	🟧	🟥	🟧	🟥	🟥	🟥	🟥	🟥
	🟩	🟧	🟩	🟩	🟧	🟧	🟩	🟧
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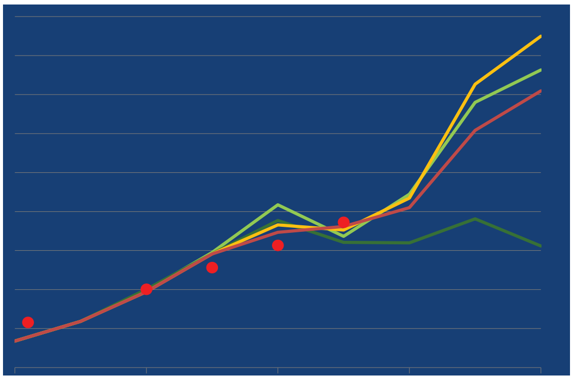
	🟩	🟧	🟧	🟧	🟧	🟩	🟥	🟧
	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

To demonstrate results more clearly, and to differentiate between the potential roles in each region, we have assigned scores to the duration of the relative and absolute bridges and the MFWFM PG UIF NBYJNVN SFMBUJWF JODSFBTF JG BOZ These criteria are set out in Table 13 and the WBMVFT JO 5BCMF IBWF CFFO DPMPVSFE UP SFÏFDU these. Finally, the scores from each criterion are combined into a single value with equal weighting BUUBDIFE UP FBDI 5IF NBYJNVN TDPSF B SFHJPO DBO UIVT BDIJFWF JT TJY BOE UIF NJOJNVN [FSP

We now interpret the role that natural gas can play in each region based on this total; this is also TIPXO JO 5BCMF *G B SFHJPO TDPSFT ÎWF PS NPSF XF DPODMVEF UIBU UIFSF JT BO FYUFOEFE BOE TUSPOH role for natural to act as a bridge or transition fuel; if it scores either three or four then gas has a more diminished role in a decarbonised energy system but still maintains a good potential to act as a transition fuel; if it scores two or less then there is a very limited or no role of gas to act as a transition fuel. The qualitative description of the role gas can play is thus also included in Table 14. These are admittedly somewhat subjective criteria and scores, however they span the full range of results, and provide a good overview of the manner in which natural gas can be seen to be acting in each region in Figures 29 and 30.

When CCS is available, natural gas plays an important or strong bridging role in four regions: China, Europe, India and Japan and South Korea. Its role as a transition fuel in the United States is also evident, but consumption falls in absolute terms from a relatively early stage. In contrast in Other Developing Asia and Australia, absolute gas consumption rises for a longer period than in the United States, but this drops below the growth in consumption in REF at an earlier stage. In the United States, Other Developing Asia and Australia, we therefore conclude that gas has good potential to act as a bridging fuel, but that this is more limited than in some other regions.

In other regions, such as Africa, Central and



DVSSFOUMZ CFJOH FYIJCJUFE JO NBOZ SFHJPOT BXBZ from coal-based power generation. A scenario with no GHG emissions reduction may not therefore be the best choice for comparison. If a scenario is chosen that results in a lower temperature rise or contains a non-zero global CO_2 UBY GPS FYBNQMF 3ºC scenario, then the advantage (from a climate perspective) conveyed by consuming additional gas SPMF JT TJHOJÎDBOUMZ MFTTFOFE

5IF ÎGUI BOE ÎOBM DBWFBU JT UIBU UIF XBT OPU FYIJCJUFE CZ BMM SFHJPOT play a bridging role in some regions but not in others. Of the 13 regions studied, gas had limited PS OP QPUFOUJBM UP BDU BT B USBOTJUJPO GVFM JO TJY (Africa, Canada, Central and South America, the .JEEMF &BTU BOE .FYJDP B HPPE QPUFOUJBM JO UISFF (Australia, Other Developing Asia, and the United States), and a strong potential in four (China, Europe, India, and Japan and South Korea). Again this is dependent on the availability of CCS, with natural gas only remaining a strong bridge in China if CCS is not available.

Finally, we found that there was very little difference in shale gas production levels under different long-term emissions mitigation targets. Production in a 2 ºC scenario was very similar to that in a 3 ºC scenario and indeed a 5 ºC scenario, FYDFFEJOH 5DN ZFBS JO BMM OPU M

However, in a 2 ºC scenario that did not allow CCS, shale gas grew to just under 700 Bcm/year by 2030, TUJMM B TJHOJÎDBOU MFWFM PG HSPX BQQSPYJNBUFMZ U 2050. These results are, however, sensitive to the relative cost assumptions of shale gas compared with other conventional and unconventional sources and to the assumed levels of fugitive FNJTTJPOT GSPN TIBMF HBT QSPEVDU issue is an area of particular ongoing controversy, CVU CPUI BSFBT SFRVJSF TJHOJÎDBOU before it can really be concluded that shale gas has an important role to play in the transition to a low-carbon global energy system.

Conclusion and Wider Implications for Gas Markets

7

This project has brought together two strands

References

8

AEA, 2012. Climate impact of potential shale gas production in the EU, Didcot, UK: AEA Technology. Available at: http://ec.europa.eu/clima/policies/ FDDQ EPDT @ÎOBM@SFQPSU@FO QEG <"DDFTTFE October 2014]

Aguilera, R.F. & Aguilera, R., 2012. World natural gas endowment as a bridge towards zero carbon emissions. Technological Forecasting and Social Change, 79(3), pp.579–586. Available at: www.sciencedirect.com/science/article/pii/ 4 <"DDFTTFE 'FCSVBSZ >

Allsopp, C. et al., 2012. The pricing of internationally USBEFE HBT + 1 4UFSO FE 0YGPSE

Anandarajah, G. et al., 2011. TIAM-UCL Global Model Documentation.

Anandarajah, G., Dessens, O. & McGlade, C.E., 2013. Modelling of global energy scenarios under CO2 emissions pathways with TIAM-UCL, London, UK.

Anandarajah, G. & McGlade, C.E., 2012. Modelling carbon price impacts of global energy scenarios, London, UK: UCL Energy Institute. Available at: www.theccc.org.uk/wp-content/uploads/2012/04/ UCL_2012_Modelling_carbon_price_impacts_of_ HMPCBM@FOFSHZ@TDFOBSJPT QEG <"DDFTTFE 2014]

Berman, A. & Pittinger, L.F., 2011. US Shale Gas: Less abundance, higher cost, The Oil Drum, 05 August.

Berman, A.E., 2010. Shale Gas-Abundance or Mirage? Why The Marcellus Shale Will Disappoint &YQFDUBUJPOT "WBJMBCMF BU XXX UIFPJMESVN DPN OPEF <"DDFTTFE 0DUPCFS >

BP, 2013. BP Statistical Review of World Energy. Available at: www.bp.com/content/dam/bp/pdf/ statistical-review/statistical_review_of_world_ FOFSHZ@ QEG <"DDFTTFE 0DUPCFS >

Chyong, C.C., Noel, P. & Reiner, D.M., 2010. The Economics of the Nord Stream Pipeline System, Cambridge, UK.

Clarkson Research Services, 2011. LNG trade & transport, London, UK.

Cobanli, O., 2014. Central Asian gas in Eurasian power game. Energy Policy. Available at: www.sciencedirect.com/science/article/pii/ 4 <"DDFTTFE .BSDI >

Core Energy Group, 2012. Gas transmission costs, Adelaide, Australia.

EIA, 2007. Natural gas compressor stations on the interstate pipeline network: developments since 1996, Washington, D.C., USA.

European Parliament & Council of the European Union, 2008. Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. 0GÎDJBM +PVSOBM PG UIF &VSPQFBO pp.1–43.

Helm, D., 2011. Peak oil and energy policy – a DSJUJRVF 0YGPSE 3FWJFX PG &DPOP QQ m "WBJMBCMF BU IUUQ PYSF PSH JDPOUFOU 1SFTTBCTUSBDU <"DDF 2014].

Herrmann, L. et al., 2013. Oil and Gas for Beginners, Deutsche Bank.

HM Treasury, 2003. Appraisal and Evaluation in Central Government, London, UK. Available at: www.hm-treasury.gov.uk/d/green_book_complete. QEG <"DDFTTFE 0DUPCFS >

IEA, 2011. Are we entering a golden age of gas?, Paris, France: International Energy Agency. Available at: www.iea.org/weo/docs/weo2011/ 8&0@(PMEFO"HFPG(BT3FQPSU QEG October 2014].

IEA, 2013a. Energy Balances of OECD and Non- 0&$% $PVOUSJFT "WBJMBCMF BU IUU PSH JFB FCP <"DDFTTFE 0 2014].

IEA, 2006. Optimising Russian natural gas, Paris, France.

IEA, 2013b. Resources to Reserves, Paris, France: International Energy Agency.

IEA, 2009. World Energy Outlook, Paris, France: International Energy Agency.

IEA, 2013c. World Energy Outlook, Paris, France.

IEA, 2012. World Energy Statistics, Paris, France.

IIASA, 2012. Scenarios database. Global Energy Assessment. Available at: www.iiasa.ac.at/web- BQQT FOF HFBEC <"DDFTTFE 0DUP

IPCC WGIII, 2014. Summary for Policymakers, Berlin, Germany.

Kesicki, F. & Anandarajah, G., 2011. The role of energy-service demand reduction in global climate change mitigation: Combining energy modelling and decomposition analysis. Energy Policy, 39, pp.7224–7233.

Khalaji, S., 2012. Compressor optimisation-1: Energy recovery guides natural gas pipeline system FGÎDJFODZ 0JM (BT +PVSOBM

Klett, T. & Schmoker, J., 2003. Reserve Growth of the World's Giant Oil Fields. In M. T. Halbouty, ed. Giant PJM BOE HBT ÎFMET PG UIF EFDBEF American Association of Petroleum Geologists, pp. 107–122.

Levi, M., 2013. Climate consequences of natural gas as a bridge fuel. Climatic Change, 118, pp.609–623. Available at: http://link.springer.com/10.1007/ T <"DDFTTFE 0DUPCFS >

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: www.springerlink.com/ JOEFY T [<"DDFTTFE October 2014].

.B[OFWB & 1VUJO &YQFDUFE U[illegible] Gas Deal as Crisis Forces Hand. Bloomberg.

McGlade, C.E., 2013. Uncertainties in the outlook for oil and gas. University College London.

McGlade, C.E., Speirs, J. & Sorrell, S., 2013a. Methods of estimating shale gas resources – comparison, evaluation and implications. Energy, 59(1), pp.116–125.

McGlade, C.E., Speirs, J. & Sorrell, S., 2013b. Unconventional gas – a review of regional and global resource estimates,. Energy, 55(1), pp.571–584.

Meinshausen, M., Raper, S.C.B. & Wigley, T.M.L., 2011. Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. Atmospheric Chemistry and Physics, 11(4), pp.1417–1456.

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. QEG <"DDFTTFE 0DUPCFS >

NETL, 2012. Role of alternative energy sources: natural gas technology assessment, Washington, D.C., USA.

Picard, D., 2000. Fugitive emissions from oil and natural gas activities. In Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change.

Skea, J., Ekins, P. & Winskel, M., 2011. Energy 2050 : Making the Transition to a Secure Low Carbon Energy System, London, UK: Earthscan.

Songhurst, B., 2014. LNG plant cost escalation, 0YGPSE 6, 5IF

Sorrell, S. et al., 2012. Shaping the global oil peak: A SFWJFX PG UIF FWJEFODF PO ÎFME TJ[decline rates and depletion rates. Energy, 37(1), pp.709–724. Available at: www.sciencedirect.com/ TDJFODF BSUJDMF QJJ 4 < October 2014].

Stephenson, E., Doukas, A. & Shaw, K., 2012. "Greenwashing gas: Might a 'transition fuel' label legitimize carbon-intensive natural gas development?" Energy Policy, 46, pp.452–459.

Stevens, P., 2012. The "Shale Gas Revolution": Developments and Changes, London, UK: Chatham House. Available at: www.chathamhouse.org/sites/ [illegible] QVCMJD 3FTFBSDI &OFS BOE %FWFMPQNFOU CQ @TUFWFOT Q October 2014].

Strachan, N., 2011. Business-as-Unusual: &YJTUJOH QPMJDJFT JO FOFSHZ NPEFM Energy Economics, 33(2), pp.153–160. Available at: www.sciencedirect.com/science/article/pii/ 4 9 <"DDFTTFE .BSDI >

UNFCCC, 2009. Report of the Conference of the 1BSUJFT PO JUT ÎGUFFOUI TFTTJPO IF from 7 to 19 December 2009. Part Two: Action taken CZ UIF $POGFSFODF PG UIF 1BSUJFT B session, Copenhagen: UNFCC.

UNFCCC, 2012. Report of the Conference of the Parties on its seventeenth session, held in DurW* (Oct100560004

"QQFOEJY

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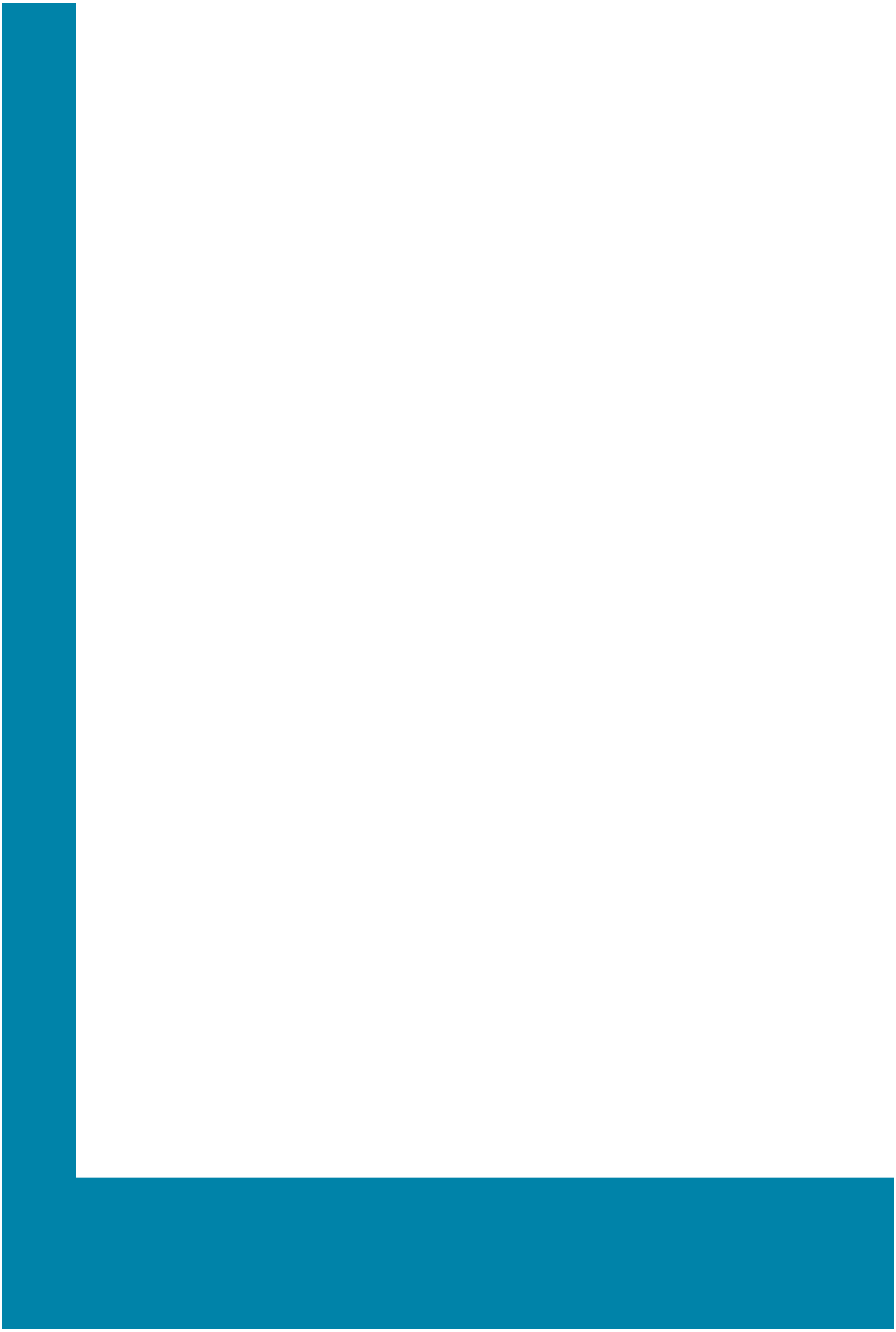

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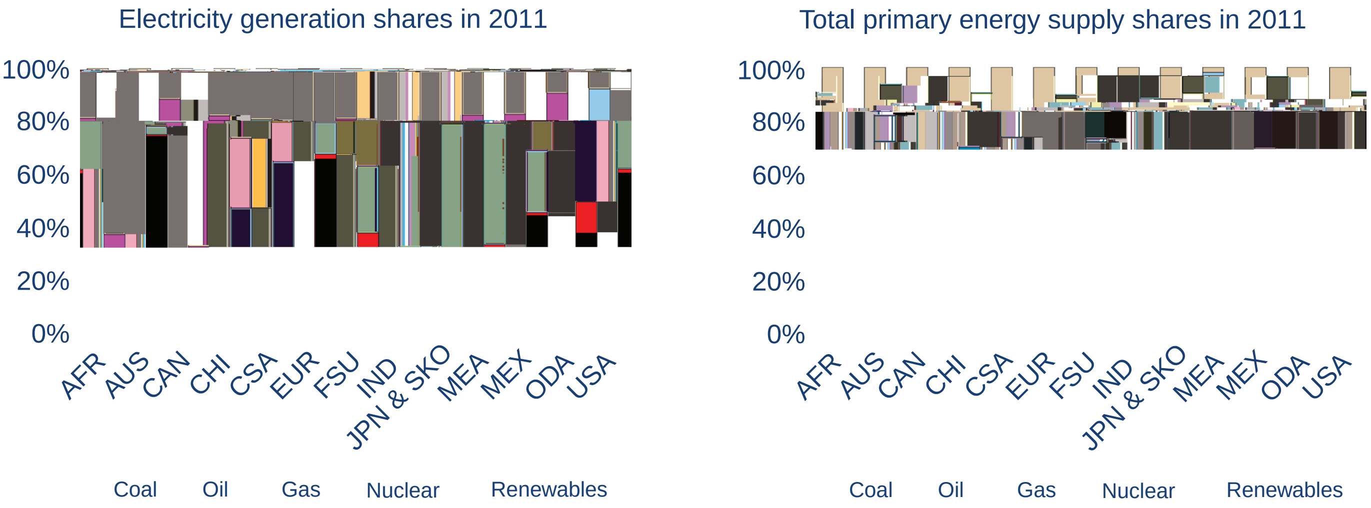
Electricity generation shares in 2011

Total primary energy supply shares in 2011

Africa – AFR; Australia and New Zealand – AUS; Canada – CAN; Central and South America –CSA; China – CHI; Europe – EUR; Former Soviet Union – FSU; India – IND; Japan and South Korea – JAP 4,0 .FYJDP m .&9 .JEEMF &BTU m .&" 0UIFS %FWFMPQJOH "TJ