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# Rapid fuel switching from coal to natural gas through effective carbon pricing

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## Abstract

Britain's overall carbon emissions fell by 6% in 2016 due to cleaner electricity production. This was not due to a surge in low-carbon nuclear or renewable sources; instead it was the much-overlooked impact of fuel switching from coal to natural gas generation. This Perspective considers the enabling conditions in Britain and the potential for rapid fuel switching in other coal-reliant countries. We find that spare generation and fuel supply-chain capacity must already exist for fuel switching to deliver rapid carbon savings, and to avoid further high-carbon infrastructure lock-in. More important is the political will to alter the marketplace and incentivise this switch, for example through a strong and stable carbon price. With the right incentives, fuel switching in the power sector could rapidly achieve on the order of 1 GtCO<sub>2</sub> saving per year worldwide (3% of global emissions), buying precious time to slow the growth in cumulative carbon emissions.

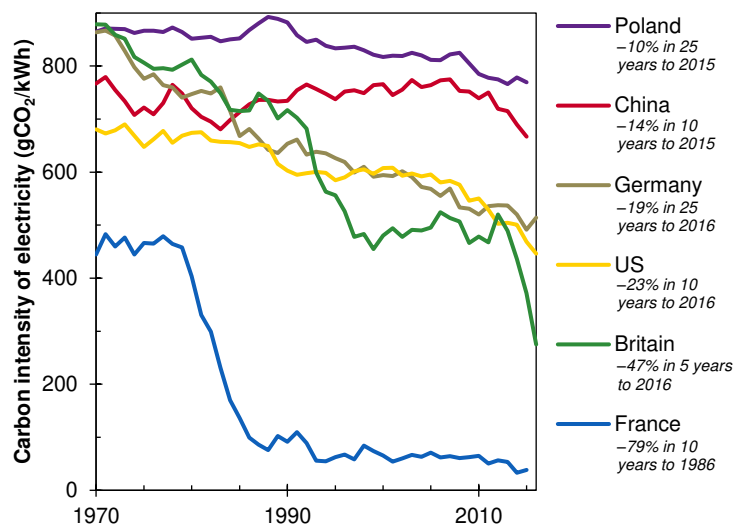
## Introduction

Global carbon emissions from fossil fuels stand at almost 37 GtCO<sub>2</sub>/yr and have grown by an average 2.4% per year so far this century<sup>1</sup>. While emissions had stabilised between 2014 and 2016 they appear to be increasing once again<sup>2</sup>, intensifying the need to reduce global fossil fuel consumption. Switching away from fossil fuels is recognised as a 'key mitigation strategy'<sup>3</sup> of 'crucial importance'<sup>4</sup> in the transport sector, but switching between fossil fuels in the power sector lacks such recognition<sup>5</sup> as it is incompatible with longer-term deep decarbonisation.

Power sector decarbonisation has received most attention with the rollout of renewables, especially wind and solar, which have grown twenty-fold in the last 15 years to reach 5% of global electricity generation<sup>6</sup>. Carbon capture and storage (CCS) is often considered an essential component of least-

31 cost decarbonisation<sup>7,8</sup>; however, it may take another three decades to achieve a 10% share of  
32 electricity generation<sup>9</sup>, amid very low expectations for CCS in the current environment<sup>10</sup> after  
33 continued delays and cancellations<sup>11</sup>. With cumulative carbon emissions being a major determinant  
34 of climate change<sup>12</sup>, any early opportunities to reduce emissions within months rather than decades  
35 deserve attention. Fuel switching between fossil fuels cannot be a long-term option as electrical  
36 generation from unabated natural gas still emits around four tenths that of coal<sup>13</sup>; and if shale gas is  
37 used, upstream methane emissions may add a further 25% to its carbon intensity<sup>14</sup>.

38 However, Britain has recently demonstrated the short-term impact of fuel switching. Displacing coal  
39 with natural gas reduced per-capita annual emissions by 400 kgCO<sub>2</sub> between 2015 and 2016, equal to  
40 6% of national emissions<sup>15</sup>. Given the long-lived nature of energy systems and their endemic inertia,  
41 this rate of change is remarkable in the absence of any major accident or disaster. Figure 1 puts these  
42 changes in context, against market-led fuel switching in China and the US, renewables deployment in  
43 Germany, and incremental efficiency improvements in Poland. The unprecedented deployment of  
44 nuclear power lowered French carbon intensity by 40 g/kWh each year for a decade (1977–1986)<sup>16,17</sup>.  
45 Fuel switching can proceed faster, but not so far: Britain’s carbon intensity fell by 85 g/kWh in 2016,  
46 but its potential is close to exhaustion as coal is almost eliminated.



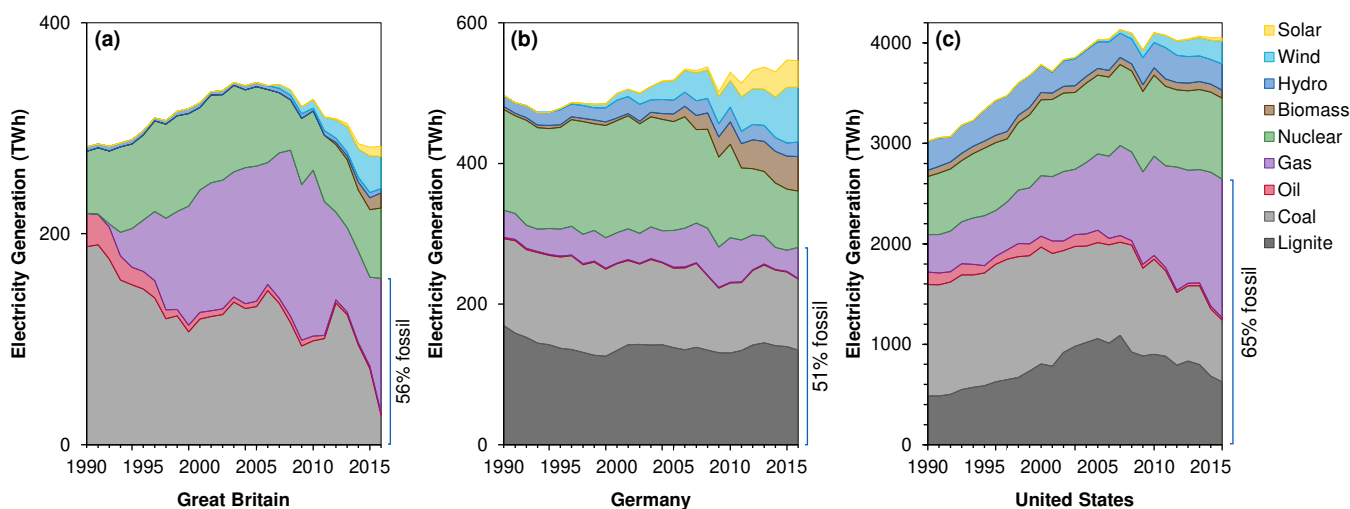
47

48 **Figure 1: Carbon intensity of electricity generation in six countries over the last half-century.** Carbon intensity for gross  
49 electricity output (not accounting for losses in transmission and distribution). The legend indicates the depth and duration of  
50 sustained reductions in emissions intensity within each country. Data from refs. <sup>16,17</sup>.

51 This Perspective argues that with the right conditions, both in terms of pre-existing infrastructure and  
52 political will, switching away from coal has an important role to play in the rapid early decarbonisation  
53 of power systems. This provides immediate benefits to other sectors, which will decarbonise faster  
54 through electrification due to lower associated emissions.

## 55 Britain's power generation

56 Coal was the largest source of electricity generation for the first hundred years of Britain's power  
 57 system. This changed in the early-1990s (Figure 2) when the newly-liberalised market invested in  
 58 combined cycle gas turbines (CCGTs), for reasons unrelated to carbon mitigation<sup>18</sup>.



59 **Figure 2: Electricity generation by fuel type in three countries over the last 25 years.** Electricity generation over time for (a)  
 60 Great Britain, (b) Germany and (c) the US. Shares of fossil fuel generation are indicated by the bracketed regions. Imports are  
 61 not included, waste is included with biomass. Between 2014 and 2016 coal + lignite generation fell by 5% in Germany, 22%  
 62 in the US and 70% in Britain. Data from refs. <sup>19,20,56,85</sup>.

63 This 'dash-for-gas' in Britain was not replicated in Germany or elsewhere in Europe, and although  
 64 termed a 'dash' it took eight years (1991–99) for new gas capacity to be built and halve coal's share  
 65 of generation<sup>19</sup> from 66% to 34%. Over the last decade, the US has shifted away from coal and lignite<sup>20</sup>  
 66 as shale gas production significantly reduced the price of natural gas. More recently, the combination  
 67 of fuel switching and coal plant retirements in Britain has seen coal's generation share fall three-  
 68 quarters to 9% in just four years (2012–16); helping to halve power sector emissions from 158 MtCO<sub>2</sub>  
 69 in 2012 to 78 MtCO<sub>2</sub> in 2016. This fuel switch drove the largest ever annual reduction in British power  
 70 sector CO<sub>2</sub> emissions<sup>21</sup> of 25 MtCO<sub>2</sub> in 2016.

71 Figure 2 shows that renewable generation expanded rapidly over the last decade to supply nearly a  
 72 fifth of Britain's electricity. However, the fall in coal generation between 2015 and 2016 was filled  
 73 entirely by natural gas: coal output fell 46 TWh and gas output increased 43 TWh, while zero-carbon  
 74 renewables changed by less than 1 TWh due to underlying weather conditions<sup>22</sup>. For context, Britain's  
 75 switch from coal to gas in 2016 was greater than all other European countries combined<sup>23</sup>.

76 If sustained, this rapid reduction arguably puts Britain well ahead of its near-term carbon reduction  
 77 trajectory, as it could now beat its carbon targets for 2018–22 within the timeframe of the 2013–2017  
 78 carbon budget<sup>24</sup>. However, as power sector emissions are part of the EU Emissions Trading Scheme  
 79 (referred to as the traded sector), the net UK carbon accounting<sup>25</sup> means that these reductions can be

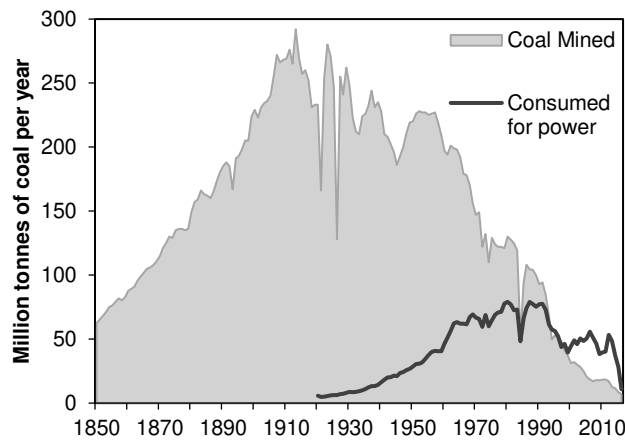
80 'exported' from the power sector as a surplus to other parts of the traded sector (e.g. heavy industry)  
81 potentially in other countries in Europe. Under agreed carbon accounting rules, they cannot be  
82 allocated to, or purchased by the non-traded sectors in Britain (e.g. domestic transport or heat) to  
83 provide additional carbon headroom<sup>26</sup>. Nevertheless, the significant reduction in electricity carbon  
84 intensity provides a direct benefit for decarbonising these sectors through electric vehicles and heat.

## 85 Britain's commitment to reduce coal power

86 During the run up to COP21 in Paris, the British government began consulting on the phase-out of  
87 unabated coal by 2025<sup>27,28</sup>, marking the world's first commitment to abandoning coal power<sup>29</sup>.  
88 Although this deadline helps frame the Government's commitment to decarbonisation, there is  
89 concern that early power station closures pose an unacceptable security of supply risk. From another  
90 perspective, it is felt increasingly important to remove unabated coal as soon as is practical to free up  
91 its market share for new, cleaner generation<sup>30</sup>.

92 Scheduling the demise of Britain's coal generation has been eased by the fleet's age (80% are over 30  
93 years old), and tightening air pollution controls such as the Industrial Emissions Directive<sup>31</sup>. Half of  
94 Britain's coal capacity (14.3 GW) closed in the 5 years to 2017, and those that remain have historically  
95 low utilisation. Coal provided less than 10% (28 TWh) of electrical generation in 2016; a smaller  
96 contribution than wind (30.5 TWh) and less than solar generated in Germany (37.5 TWh)<sup>32</sup> over the  
97 same year.

98 Britain is therefore on track to become the first major economy to transition away from coal after  
99 centuries of production and consumption (Figure 3). The latter fell to 12 Mt in 2016<sup>33</sup>, levels not seen  
100 since 1935<sup>34</sup>. The rate of this change is unprecedented; it took 14 years for power sector coal demand  
101 to increase from 12 to 28 million tonnes per annum (1936 to 1950), but only 1 year to make the reverse  
102 transition (2015 to 2016). Britain could be the first country to leave its coal reserves unburnt in the  
103 ground<sup>35</sup>, and in November 2017 it set out a global alliance to end coal power generation<sup>36</sup>. This would  
104 have been inconceivable to policymakers even a generation ago, when coal, nuclear and oil generation  
105 powered the country<sup>18</sup>.



106

107 *Figure 3: Quantity of coal mined and consumed for power generation in Britain. Power sector data from ref. <sup>19</sup> and coal*  
 108 *production data from refs. <sup>33</sup> and <sup>34</sup>.*

### 109 Factors that enabled Britain’s rapid fuel switch

110 Britain’s experience of fuel switching can be viewed as a policy success, albeit at a rate that was better  
 111 than anticipated. We suggest four factors were necessary to achieve this rapid fuel switch: first, gas  
 112 generation plants were already built and had spare underutilised capacity; second, existing fuel supply  
 113 infrastructure could cope with the increased power sector gas demand; third, the political will was  
 114 available to intervene in markets to incentivise the switch, penalising coal vs. gas generation via an  
 115 effective carbon price; Finally, coal and gas prices were sufficiently close so that switching did not  
 116 inflict large price rises on electricity consumers (a carbon price of £50/t was needed to incentivise fuel  
 117 switching in 2013, compared to £16/t in 2016)<sup>13</sup>.

118 Renewable generation has also rapidly increased in Britain (Figure 2), lowering emissions over the last  
 119 decade. However, significant emissions reductions only began in 2013 due to the declining share of  
 120 coal as carbon prices began to rise, as will be discussed in detail below.

121 While putting a price on carbon enabled the fuel switch in 2015 to be rapid, the development of this  
 122 policy and the enabling conditions and the investment in generation and infrastructure for the switch  
 123 to take place were decades in the making. The EU Large Combustion Plant Directive (2001)<sup>37</sup> and  
 124 Industrial Emissions Directive (2010)<sup>31</sup> aided in closing half of Britain’s coal capacity; while the Climate  
 125 Change Act (2008)<sup>38</sup> and Electricity Market Reform (2013)<sup>39</sup> laid the foundations for the Carbon Price  
 126 Support scheme.

### 127 Putting a price on carbon

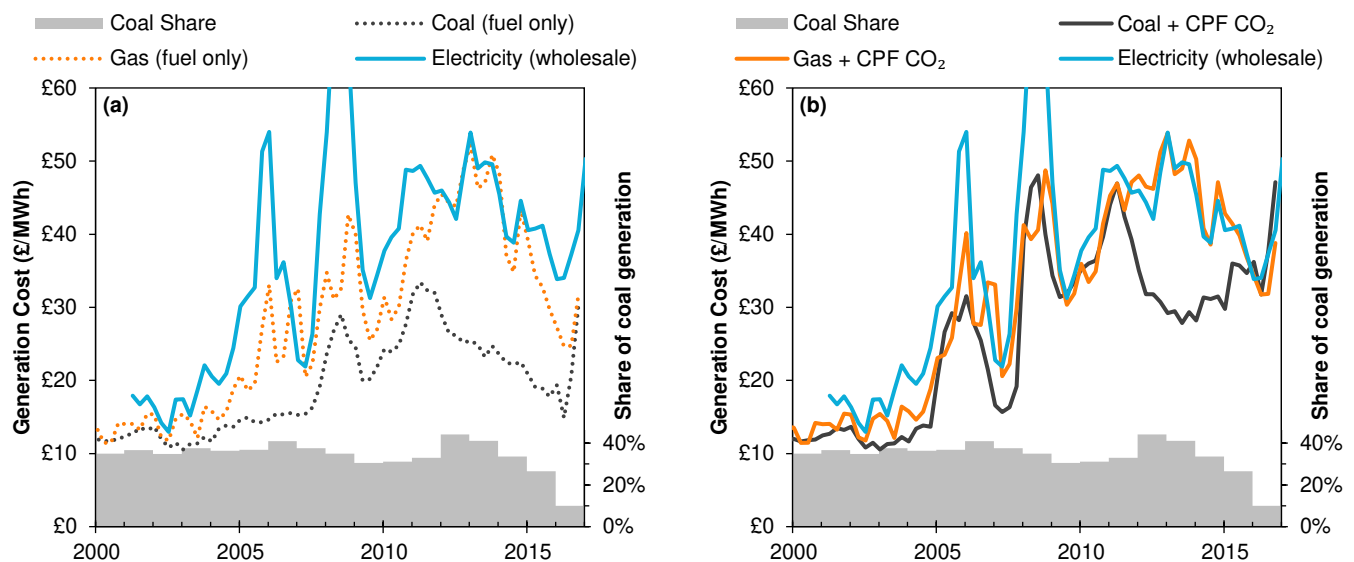
128 Our view is that the primary driver for coal’s substitution in 2015–16 was the higher price placed on  
 129 carbon emissions. Since 2005 British power stations were subject to the EU Emissions Trading Scheme

130 (ETS) but it delivered carbon prices that were too weak to drive sustained lower-carbon investment<sup>40-</sup>  
131 <sup>43</sup>. To address this, Britain introduced the Carbon Price Support (CPS) policy in 2013 which required  
132 power-sector emitters to pay a top-up price to a Carbon Price Floor (CPF) determined by  
133 policymakers<sup>44</sup>. This aims to provide generators with the certainty of a more stable (but higher) price  
134 of CO<sub>2</sub> than delivered by the EU-wide market alone.

135 This CPS policy is still subject to regulatory risk as the floor price can be changed. Its initial trajectory  
136 was rising towards £70/tCO<sub>2</sub> in 2030; however, successive announcements have frozen the CPS rate  
137 at its 2017 level of £18/tCO<sub>2</sub> at least until 2021. While this suggests diminished ambition in the face  
138 of cost sensitivities, it should be compared to an EU-ETS price of approximately €5/tCO<sub>2</sub> throughout  
139 2016.

140 Debate continues about the floor price<sup>45-47</sup>. Whilst it has been effective in promoting the switch from  
141 coal to existing natural gas generation, it has failed to incentivise construction of new low-carbon  
142 generation, which continues to require other forms of financial support. The cost to consumers can  
143 be roughly approximated from Figure 4a as the gap between the actual electricity price and the  
144 estimated cost of the marginal fuel (whichever is more expensive, gas or coal). We estimate the  
145 carbon price floor has added in the region of 0.7 p/kWh to retail prices (~5%) during 2016. This rough  
146 estimate is indeed comparable to government analysis<sup>48</sup> and estimates for UK industry<sup>49</sup>. This price  
147 rise is very modest considering the ~25% reduction in power sector emissions it facilitated in just one  
148 year.

149



151 **Figure 4: Wholesale price of electricity in Britain with the competitive benchmark based on fuel and carbon prices. (a)**  
 152 **Electricity prices compared with the estimated cost of generation from coal and gas with no carbon price. (b)**  
 153 **The same comparison including the prevailing carbon price (CPF CO<sub>2</sub>) in Britain. The solid grey shading plots the share of total electricity**  
 154 **generation from coal. Generation cost consists of fuel combusted (divided by conversion efficiency) and carbon emitted**  
 155 **(multiplied by carbon price), neglecting other aspects such as maintenance and network charges. Prices and costs have**  
 156 **quarterly resolution, the coal generation share has annual resolution. Carbon price data from refs.<sup>44</sup> and <sup>86</sup>, fuel price data**  
 157 **from ref. <sup>87</sup>, electricity price and coal share data from ref. <sup>13</sup>. Electricity prices represent the day-ahead spot market.**

158 The costs of electricity generation are shown in Figure 4, highlighting the falling cost of gas relative to  
 159 coal since 2014. However, coal would still be the cheapest form of generation with the European ETS  
 160 carbon price, despite the sharp rise in international coal prices through 2016 (due to China cutting  
 161 production by 10%)<sup>50</sup>. Instead, the CPF allowed gas generation to become equivalent or cheaper since  
 162 the beginning of 2016 and to displace coal's share of generation. In terms of historical precedence,  
 163 the carbon price in Britain has been raised back to its level in 2008. In the rest of Europe, it remains  
 164 at just one-third of its peak.

165 Fuel switching is not unidirectional, and could equally be reversed while coal generation capacity  
 166 remains available over the coming years, helped by capacity market payments. All this would take is  
 167 another shift in relative fuel prices or a weakening of the carbon price to increase coal's annual market  
 168 share.

## 169 Leaving the markets to it

170 Britain's experience shows that liberal markets can rapidly adjust to well-timed well-aimed policy  
 171 signals. Policy is not an essential ingredient though, as America demonstrates that a confluence of  
 172 market factors can drive fuel switching alone, albeit at a slower pace.<sup>51-53</sup> Since 2005, natural gas  
 173 prices have fallen 70% compared to 25% for coal due to increased production and the inability to



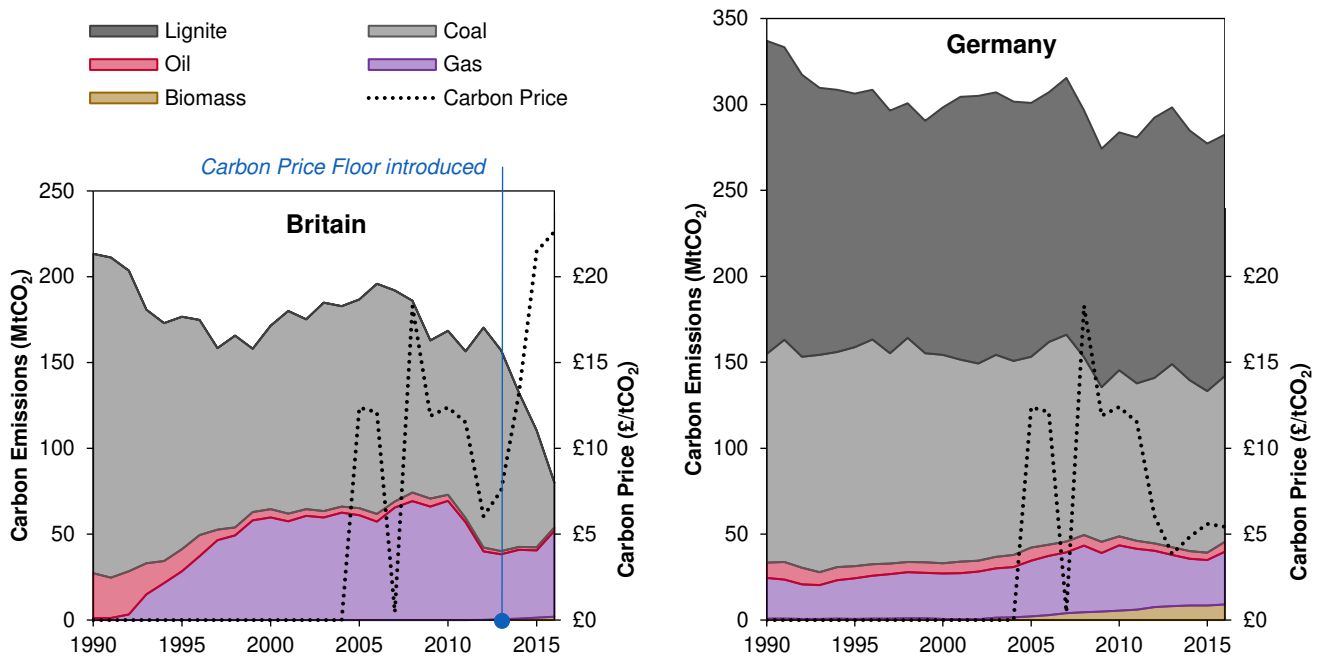
174 export shale gas<sup>6</sup> (due to insufficient infrastructure). This has lowered the US average carbon intensity  
175 of electricity by a quarter (see Figure 1), with a 5 percentage point swing from coal to gas<sup>20</sup> occurring  
176 in 2015, reducing power sector emissions by over 130 Mt<sup>54</sup>.

177 The political landscape changed with the election of President Trump in November 2016, suggesting  
178 ongoing tensions between Federal efforts to revive an ailing coal sector, and many State policies that  
179 focus on decarbonisation. Carbon pricing at a federal level which would accelerate fuel switching from  
180 coal to natural gas is therefore improbable under the Trump administration. The US has a complex  
181 range of political drivers from federal environmental regulations impacted by sector lobbying, layered  
182 with further political drivers at state level. Within this melange of political and market forces, it is  
183 difficult to suggest future levels of fuel switching with any degree of certainty. Federal regulations  
184 have switched back and forth to favour different technologies, which suggests the benefit of having  
185 legal multi-decadal targets to aim for. Britain is not immune from lobbying and switching regulations  
186 back and forth to suit different technologies, but it has pioneered the use of long-term legal targets in  
187 the 2008 Climate Change Act<sup>38</sup>. This has kept the long-term ambition on track regardless of the change  
188 of policy makers and the political pressure to rescind policies that become unpopular with core voters.

## 189 Potential for fuel switching in Germany

190 Germany is regarded as a champion of renewable energy for its extensive investment in wind and  
191 solar power. However, it has had limited success in decarbonising its power sector, with emissions  
192 down 15% since 1990, compared to Britain's reduction of 61%. Figure 5 shows that Germany's lack of  
193 progress is due to continued reliance on lignite and hard coal for >40% of electricity supply.

194



196 *Figure 5: Power sector CO<sub>2</sub> emissions by fuel source in Germany and Britain. The carbon price in each country is overlaid as*  
 197 *a dotted line, showing the marked difference since the introduction of the UK's Carbon Price Floor in 2013. It is our view that*  
 198 *this was the major additional factor that caused the rapid shift from coal to natural gas generation after 2013. Generation*  
 199 *mix data from refs. <sup>19</sup> and <sup>56</sup>, emissions intensities from refs. <sup>32</sup> and <sup>13</sup>, and carbon prices from refs. <sup>44</sup> and <sup>86</sup>.*

200 Germany is self-sufficient for lignite but imports 89% of its hard coal<sup>55</sup>, as its geology makes local  
 201 production internationally uncompetitive. Import dependency for natural gas is similarly 90%,  
 202 although only one-sixth of demand is from the power sector as gas is primarily used for heating<sup>56</sup>.  
 203 Around 15bcm/year (~150 TWh/year) of spare capacity exists in the Nordstream pipeline for increased  
 204 gas supplies<sup>57</sup>, with an additional 55bcm/year (540 TWh/year) if Nordstream 2 is constructed. At a  
 205 national level, it seems the fuel supply infrastructure has the potential to accommodate significant  
 206 levels of fuel switching.

207 However, several factors temper Germany's desire to take this route, not least the security  
 208 implications of swapping indigenous lignite to imported natural gas. Germany's decision to remove  
 209 nuclear generation provides an additional challenge: installing 60 GW of wind and solar power in the  
 210 last decade has done little more than offset the lost output from the 10 GW of retired nuclear power<sup>32</sup>.  
 211 Both considerations were not applicable to Britain, which has no lignite mines, and, in contrast to  
 212 Germany, is embracing new nuclear build. Germany is a fascinating interaction of political economy  
 213 interests, with a lignite lobby that capitalises on security of supply and cost arguments for Germany's  
 214 energy transition. However, without the development of carbon capture and storage in Germany  
 215 (which currently seems highly challenging), lignite generation will at some point be impossible to  
 216 reconcile with decarbonisation targets. Britain's experience shows that Germany's fuel mix could be  
 217 rapidly changed given their pre-built but underutilised gas generation capacity.

218 Germany has 24 GW of gas-fired power stations, compared to 28 GW of hard coal and 21 GW of  
219 lignite<sup>32</sup>. In recent years, nearly-new gas power stations have been mothballed after proving  
220 unprofitable, and eventually exported to the Middle East<sup>58</sup>. This is because gas capacity lies mostly  
221 unused, with 18% utilisation compared to 40% for hard coal and 74% for lignite in 2016<sup>56</sup>. An  
222 additional 155 TWh of electricity could be produced if this gas generation capacity were utilised at  
223 80%, sufficient to completely eliminate hard coal plus four-tenths of lignite production, which would  
224 cut Germany's power sector emissions by around a quarter, or 62 MtCO<sub>2</sub> per year.

225 Greater emissions savings would result from displacing lignite. However, this would increase primary  
226 energy import dependency; whereas switching from hard coal to natural gas would simply switch one  
227 type of energy imports for another, introducing a different set of risks.

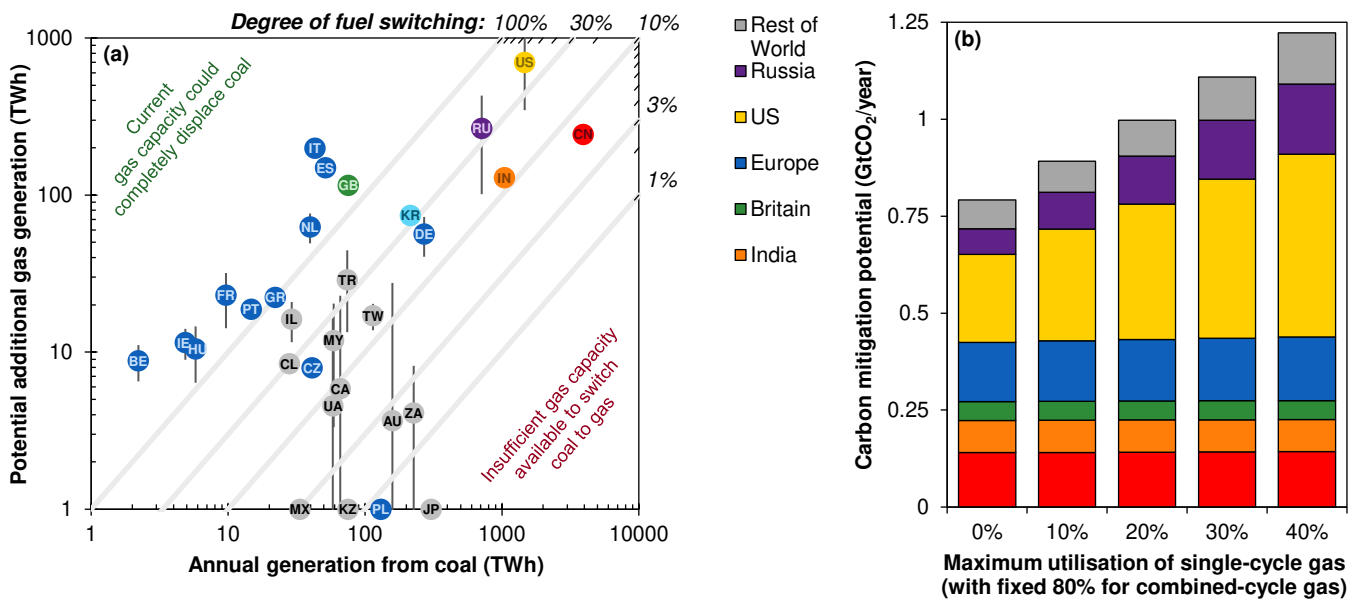
## 228 Potential for fuel switching globally

229 Quantifying a more accurate global potential for fuel switching require a detailed country-by-country  
230 analysis of infrastructure, generation, security of supply, demand, prices, and political interests; and  
231 will be a valuable area of future work. Nonetheless, the broad order-of-magnitude can be estimated  
232 using existing statistics for annual generation and installed generating capacity. We estimate the  
233 potential for fuel switching in the 30 largest coal consuming nations (covering 97% of global coal  
234 capacity) by compiling the amount of coal and lignite generation in 2015, and comparing this to the  
235 additional generation that could come from gas in each country. This is based on existing,  
236 underutilised gas generation; disregarding the option of building new capacity. The maximum gas  
237 generation potential assumes that combined-cycle gas turbines (CCGTs) could run up to 80%  
238 utilisation (limited by availability and downtime), while open-cycle (OCGTs) and steam boiler stations  
239 would be limited to 0–40% utilisation (due to economic rationale). Displacing coal with single-cycle  
240 (rather than combined-cycle) gas stations would yield half the carbon savings due to their lower  
241 efficiency and thus higher carbon intensity. We assume CO<sub>2</sub> emissions of 405 g/kWh for CCGTs and  
242 710 g/kWh for OCGTs, relative to 1025±55 g/kWh for national coal fleets<sup>16</sup>. Sources, details and  
243 justification are given in the Methods section.

244 Figure 6a shows the potential for fuel switching across the OECD and coal-reliant developing countries.  
245 Many European countries (including Britain) have over-built power systems with sufficient idle gas  
246 capacity to completely eliminate coal, at least at the annual aggregate level. Of the largest coal  
247 consumers, Russia and the US could convert 40–50% of their coal generation to gas, but China and  
248 India could only displace 6–12% due to the vast scale of their coal fleets.

249 Poland depends on solid fuels for over 90% of its electricity, and lacks the pre-existing gas plants to  
 250 take over market share<sup>59</sup>. Japan is still gripped by a capacity shortage in the wake of the Fukushima  
 251 disaster and shutdown of its nuclear fleet, thus its gas stations are running close to capacity already.

252 Figure 6b shows that if fuel switching was fully realised in these 30 countries, annual emissions could  
 253 fall by 0.8–1.2 GtCO<sub>2</sub>, around 3% of global emissions. Reductions in China, India and Europe amount  
 254 to 440 MtCO<sub>2</sub> per year, and are insensitive to the utilisation of single-cycle plants as these make up  
 255 only a fifth of their gas fleet. The mitigation potential in the US and Russia is more sensitive to the  
 256 assumed utilisation, as OCGTs and steam boilers form half their gas capacity.



257 **Figure 6: Estimation of the carbon mitigation potential from fuel switching in 30 countries.** (a) Comparison of output from  
 258 coal power stations in 2015 with the potential for additional gas generation, if existing combined-cycle gas plants operated  
 259 at 80% utilisation and single-cycle plants at 20% (with bars showing 0% to 40%). (b) The annual greenhouse-gas emission  
 260 savings if the identified potential for fuel switching was realised across these countries, showing the sensitivity to the  
 261 utilisation of single-cycle gas plants. In panel (a), countries are identified using their two-letter ISO codes, and diagonal lines  
 262 highlight the share of coal that could be displaced by gas. Colours are used to group countries into the geographic regions  
 263 listed in the legend of panel (b). The four countries with zero potential for additional gas output (Mexico, Kazakhstan, Poland  
 264 and Japan) are shown below the axis. Data from sources listed in the Methods section.

## 265 No Silver Bullet

266 While this analysis is only a first-order approximation (noting the simplifications listed in the Methods  
 267 section), it suggests that fuel switching in the power sector could provide a significant boost to global  
 268 decarbonisation. However, fuel switching is no silver bullet, and many barriers can explain why only  
 269 a small percentage of the estimated potential has been realised thus far.

270 Fuel switching will change supply-chain and energy security risks, and in many countries would create  
 271 political tensions by increasing import dependency for primary energy. Although employment in the  
 272 coal sector has fallen dramatically in many western countries, policies which are seen to further  
 273 decimate domestic mining industries will face opposition, as seen in America. Over the longer term,

274 politicians must grapple with the consequences of transitioning away from solid fuels; notably how to  
275 engage and retrain affected mining communities where coal production is culturally significant, as well  
276 as a source of employment.

277 There are also risks with carbon leakage in highly interconnected markets such as Germany<sup>60,61</sup>. A  
278 strong carbon price to promote fuel switching can reduce within-country emissions, but may also shift  
279 electricity production (and thus carbon emissions) to areas subject to a lower carbon price. Britain  
280 now imports high-carbon electricity from the Netherlands, where coal usage increased 40% and  
281 generators pay one-fifth the carbon price. Supranational harmonisation of carbon pricing is needed  
282 to avoid the 'offshoring' of power sector emissions. Other considerations, such as the level of methane  
283 leakage in the natural gas supply chain must also be carefully assessed<sup>62,63</sup>.

284 Carbon pricing however is not a blanket policy that will work everywhere. In countries that lack the  
285 gas infrastructure such as Poland or Japan, raising a carbon price would in the short term be no less  
286 blunt than a blanket tax on electricity. In the longer term, a careful balance is needed to redirect how  
287 existing infrastructure could be used without going so far as to incentivise building new gas  
288 infrastructure and avoidable carbon lock-in. If limiting global temperature rise to 2°C requires no more  
289 carbon-emitting electricity generation to be built<sup>64</sup>, the distinction between utilising existing gas  
290 generation versus investing in additional capacity is of critical importance<sup>65,66</sup>.

## 291 Conclusions

292 Switching between fossil fuels can only ever be a temporary stepping stone towards a low-carbon  
293 energy system. Its potential is bounded by the scale of existing coal and gas infrastructure, and natural  
294 gas is incompatible with deep decarbonisation<sup>67,68</sup> unless carbon capture and storage emerges from  
295 its 'valley of death'<sup>11</sup>. If spare capacity already exists, then fuel switching does not require several  
296 years to amount to material emissions savings, unlike other key options (renewables, nuclear,  
297 efficiency improvements). The 'quick win' is provided simply by using pre-existing infrastructure more  
298 effectively.

299 Britain's example highlights the effectiveness under certain key circumstances of placing a modest,  
300 but stable, £18/tCO<sub>2</sub> on carbon, and the speed with which the power sector generation changed in  
301 response to such a signal; it switched 15% of its generation mix (45 TWh) in a single year, saving 25  
302 MtCO<sub>2</sub>. Fuel switching can demonstrably achieve very rapid carbon reductions. In comparison  
303 renewables took six years to grow from 4% to 19% of Britain's generation (a 45 TWh/yr increase),  
304 saving approximately<sup>13</sup> 22 MtCO<sub>2</sub>. It will be at least 10 years before new nuclear capacity will be built  
305 in Britain<sup>58</sup>, which would require three projects the size of Hinkley Point C to save 27 MtCO<sub>2</sub> per year<sup>69</sup>  
306 to fuel switch from natural gas (as coal will no longer be in the system).

307 Fuel switching can also be a cost-effective and convenient form of decarbonisation. If driven solely by  
308 market forces it will lower bills; if policy support alters the balance between closely-priced fuels, it can  
309 have minimal impact on consumers, as seen in Britain. Natural gas retains the energy system benefits  
310 of being a fuel: controllable and dispatchable generation, and extensive storage infrastructure with  
311 days to weeks of capacity, rather than minutes to hours for electrochemical and thermal storage<sup>70,71</sup>.  
312 Controllable flexibility is increasingly desirable to accommodate greater levels of variable renewable  
313 energy generation, especially so if coal generation is simultaneously being retired.

314 Anthropogenic carbon emissions had almost plateaued in 2016<sup>2</sup>. The next, momentous step – for  
315 emissions to decrease – could be catalysed by a concerted global effort to switch away from coal to  
316 natural gas. Our initial examination suggests the top 30 coal consuming countries could prevent 1 Gt  
317 of CO<sub>2</sub> emissions from entering the atmosphere annually; with a central estimate that 20% of the  
318 world’s coal could be switched to gas using existing, under-utilised infrastructure (the range is 13%  
319 with no OCGT up to 27% with them running at 40% utilisation). This provides an immediate benefit  
320 to slow the increase in cumulative carbon emissions, buying all-important time for other sectors to  
321 catch up, and providing cleaner electricity with which to decarbonise them. Any effort to front-load  
322 emissions reductions will ease the pressure on future generations who are faced with removing  
323 emissions from the atmosphere<sup>72</sup>. However, it is vital to cumulative emissions that the gains of early  
324 decarbonisation from fuel switching are not squandered by the extended use of gas generation as a  
325 substitute for the necessary increase in low-carbon technologies.

326 The potential for rapid and material global emissions reductions appears to have gone unnoticed thus  
327 far; it is about time that the benefits of fuel switching received greater attention.

328

## 329 Methods

330 **Overview.** We perform a high-level evaluation of the carbon mitigation potential of switching from  
331 coal to gas in the power sector based on statistics for annual generation and installed capacity. The  
332 aim is to produce an order-of-magnitude estimate that motivates the discussion around fuel switching  
333 in the power sector. A more nuanced approach would form the basis of a more detailed exploration  
334 of the potential of fuel switching.

335 The calculation for a given country can be summarised by four stages:

- 336 1. Find the historic annual production from coal and gas plants;
- 337 2. Find the installed capacity of gas plants, broken down to combined-cycle and single-cycle;
- 338 3. Estimate the maximum potential output from the gas fleet, and thus how much coal could be  
339 displaced by gas;

340 4. Estimate the carbon intensity for the coal and gas fleet, and thus the carbon savings from  
341 switching between them.  
342

343 To summarise, we assume coal stations emit  $1025 \pm 55$  gCO<sub>2</sub>/kWh which could be displaced by  
344 combined-cycle gas stations producing 405 g/kWh or single-cycle stations producing 710 g/kWh. We  
345 assume combined-cycle gas plants could run baseload with 80% utilisation, and test a range of  
346 utilisations for single-cycle plants from 0% (not being used at all) up to 40%.

347

348 **Coverage.** We consider thirty countries from the OECD and larger developing nations, which together  
349 possess 1900 GW of coal capacity (97% of listed global capacity) and 1100 GW of gas capacity (83%).  
350 The choice to study thirty countries was arbitrary (inspired by an anonymous peer reviewer's  
351 comments), as a trade-off between tractability and comprehensiveness. The countries are listed in  
352 Figure 6 by their ISO codes, and are listed in full in Supplementary Table 1.

353

354 **Terminology.** *Coal* is used as shorthand for both coal and lignite together. *Combined-cycle* is  
355 shorthand for combined-cycle gas turbine (CCGT, or also NGCC). *Single-cycle* is shorthand for both  
356 steam boilers and open-cycle gas turbines (OCGTs, or also combustion turbines).

357

358 **Data.** The annual electricity generation from coal, gas and nuclear was taken from the IEA<sup>17</sup> for 2015,  
359 which was the most recent year available. Nuclear was included to provide a sense check when  
360 comparing fossil output to total demand, and when matching capacity and production statistics.

361 The installed generating capacity was taken from Platts<sup>73</sup> and Enerdata<sup>74</sup> for the end of 2015. The  
362 unweighted average was taken across both sources where possible to aim for a comprehensive and  
363 unbiased estimate.

364 Coal capacity was broken down by fuel type: hard coal (anthracite and bituminous), soft coal (sub-  
365 bituminous) and lignite; and by the class of steam generator: ultra-supercritical, supercritical and  
366 subcritical. Gas capacity was broken into combined-cycle and single-cycle. It was not possible to  
367 achieve the same breakdown for electricity production, so it was assumed that each countries' coal  
368 and lignite generators operate with the national-average utilisation.

369 Alignment between the output and capacity datasets was verified by calculating the utilisation of coal  
370 and gas plants (and also for nuclear power as a secondary check), ensuring that 100% was not  
371 exceeded in any country.

372 It is regrettable that a full examination of the intermediate data and results cannot be given here, as  
373 many of the inputs are derived from commercial sources. Recreating this analysis using open-access  
374 data is a logical and important next step<sup>75</sup>.

375

376 **Estimating Potential Gas Generation.** We must make an assumption about the maximum utilisation  
377 of gas power stations to estimate the potential output from a known capacity. It is unreasonable to  
378 assume a power station could operate at maximum capacity all year round, as this ignores the need  
379 for maintenance, unexpected outages, and seasonal derating due to ambient temperature.

380 We assume that CCGTs can operate as baseload generators with 80% utilisation, which equates to  
381 7,000 full-load hours per year. This is based on the median utilisation of nuclear power (traditionally  
382 a baseload generator), which was 79% across the countries we consider. The 90<sup>th</sup> percentile for  
383 nuclear utilisation across the countries was 90%. Coal and gas stations were observed with 75–85%  
384 utilisation in Japan, South Korea, Taiwan, Mexico, Poland, Netherlands and Portugal. This assumption  
385 is slightly conservative compared to the values for CCGT utilisation employed in analysis by the IEA  
386 (85%)<sup>76</sup>, EIA (87%)<sup>77</sup> and BEIS (93%)<sup>78</sup>. Their mean of 88% implies the potential for fuel switching could  
387 be one tenth higher than we estimate.

388 Single-cycle generators are not assumed to run as baseload as their lower fuel efficiency implies higher  
389 running costs. We consider a range of utilisations from 0% to 40% (0 to 3,500 full-load hours), and  
390 take 20% as a central value (1,750 full-load hours). We estimate that in 2015, single-cycle generators  
391 have around 20% utilisation in Australia, around 40% in Japan and Ukraine and over 60% in Mexico,  
392 Malaysia and South Africa.

393 We cannot directly observe the historic utilisation of single-cycle generators as the production data  
394 sources give no distinct breakdown. We therefore estimate their utilisation by assuming that CCGTs  
395 cannot exceed 80% utilisation. As a worked example: consider a country with 400 TWh annual gas  
396 generation coming from 80 GW of capacity, of which 40 GW is combined-cycle and 40 GW is single-  
397 cycle (these figures approximately represent Japan). The overall gas fleet has 57% utilisation. If the  
398 CCGTs could run at 100% utilisation they would produce 350 TWh/yr, meaning the single-cycle plants  
399 must run at 14% to deliver the annual total. Using our expectation of 80% CCGT utilisation, single-  
400 cycle plants must operate at 34% utilisation.

401 Direct observations are possible for the US gas fleet using Bloomberg data<sup>79</sup>. The average utilisation  
402 of single-cycle plants is below 10%, but this is skewed by a large number of inactive plants. One  
403 quarter of the fleet has a utilisation of over 20%. For comparison, the EIA assume 30% utilisation for  
404 conventional gas combustion turbines<sup>77</sup> and BEIS assume 22% utilisation for OCGTs<sup>78</sup>.



405 We combine the potential output from combined-cycle and single-cycle plants, then subtract off their  
406 actual production to give the amount of additional coal that could be displaced. The minimum of this  
407 potential extra gas, and the actual output from coal is then taken as the fuel switching potential –  
408 given in Figure 6a, and in Supplementary Table 1.

409 Supplementary Table 2 gives a work-through of the calculation, using stylised numbers that  
410 approximately represent Japan, Britain and the US.

411

412 **Assumptions on Carbon Intensity.** We estimate the fleet-average carbon intensity based on each  
413 country's installed technology mix. For coal this was based on the relative share of capacity using each  
414 fuel and boiler type; for gas it was based on the relative amount of additional output from combined-  
415 cycle and single-cycle plants.

416 For gas, global values from the IEA were used<sup>80</sup>: 405 g/kWh for combined-cycle gas turbines and 710  
417 g/kWh for open-cycle gas turbines (combustion turbines) and steam boilers. These agree with the  
418 capacity-weighted averages calculated by Bloomberg within the US<sup>79</sup>: 404 g/kWh for combined-cycle  
419 and 711 g/kWh for open-cycle.

420 For coal, IEA<sup>81</sup> values for each grade of fuel were combined with IEA<sup>82</sup> values for each class of steam  
421 generator, to give the matrix of carbon intensities in Supplementary Table 3. All subcritical plants  
422 were assumed to be 'new' regardless of their age, to remain conservative in estimating the carbon  
423 mitigation potential for fuel switching.

424 Bloomberg estimate the capacity-weighted average carbon intensity for US coal plants in 2015 to be  
425 965 g/kWh for hard coal, 1020 g/kWh for sub-bituminous coal, and 1075 g/kWh for lignite<sup>79</sup>. Given  
426 that the US has a 71:29 mix of subcritical and supercritical plants<sup>73</sup>, these values lie within  $\pm 3\%$  of the  
427 carbon intensities estimated using Supplementary Table 3.

428 In summary, our assumptions suggest that displacing 1 TWh of coal generation would save 0.620  
429 MtCO<sub>2</sub> using combined-cycle gas, or 0.315 MtCO<sub>2</sub> using single-cycle gas. Following on from the  
430 examples set out in Supplementary Table 2, the calculation of fleet-average carbon intensity and the  
431 mitigation potential of fuel switching are outlined in Supplementary Table 3.

432

433 **Simplifying Assumptions.** Again, it must be stressed that this is a first-order approximation, and the  
434 results presented above come with three notable caveats.

435 No consideration has been made about the time-varying nature of electricity demand. It may not be  
436 possible for combined-cycle gas stations to run with 80% utilisation if the profile of demand has

437 significant diurnal or seasonal swings, as their output cannot exceed the country's minimum demand  
438 for electricity. This minimum is around two-thirds of average demand in European countries.<sup>83</sup> We  
439 found that few countries had enough installed gas capacity for the maximum potential gas output to  
440 be more than two-thirds of annual demand, so this may not be a severe limitation. Notable exceptions  
441 were Britain, Italy and the Netherlands.

442 No consideration is given to fuel supply and transportation infrastructure. It may not be possible for  
443 some countries to supply the necessary quantity of gas to their power stations in the short-term.

444 No spatial detail is included within individual countries. The location of gas generators relative to  
445 demand centres and transmission infrastructure may limit the output of gas power stations –  
446 particularly in larger countries such as the US and China.

447 **Data Availability.** The data that support the plots within this paper are available in the Figshare  
448 repository, 10.6084/m9.figshare.5827695<sup>84</sup>. As detailed in the Methods section, much of the  
449 underlying data is proprietary – and is therefore unable to be shared by the authors.

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