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

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Abstract

Britain's carbon emissions fell by an extraordinary 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. 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 in the order of 1 $GtCO_2$ saving per year (3% of global emissions), buying precious time to slow the growth in cumulative carbon.

Introduction

Global carbon emissions from fossil fuels stand at almost 37 $GtCO_2$ and have grown by an average 2.4% per year so far this century[1]. While emissions had stabilised between 2014 and 2016 they appear to be increasing once again, intensifying the need to reduce global fossil fuel consumption. Switching away from fossil fuels is recognised as a 'key mitigation strategy'[2] of 'crucial importance'[3] in the transport sector, but switching between fossil fuels in the power sector lacks such recognition[4] 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[5]. Carbon capture and storage (CCS) is often considered an essential component of least-cost decarbonisation[6,7]; however, it may take another three decades to achieve a 10% share of electricity generation[8], and "expectations for CCS are very low in the current environment"[9] after continued delays and cancellations[10]. With cumulative carbon emissions being a major determinant of climate change[11], any early opportunities to reduce emissions within months rather than decades deserve attention. Fuel switching between fossil fuels cannot be a long-term option as electrical generation from unabated natural gas still emits around four tenths that of coal[12]; and if shale gas is used, upstream methane emissions may add a further 25% to its carbon intensity[13].

However, Britain has recently demonstrated the short-term impact of fuel switching. Displacing coal with natural gas reduced per-capita annual emissions by 400 $kgCO_2$ between 2015 and 2016. Given the long-lived nature of energy systems and their endemic inertia, this rate of change is remarkable in the absence of any major accident or disaster. Figure 1 puts these changes in context; against market-led fuel switching in China and the US, renewables deployment in Germany, and incremental efficiency improvements in Poland. The unprecedented deployment of nuclear power lowered French carbon intensity by 40 g/kWh each year for a decade (1977–1986)[14,15]. Fuel switching can proceed faster, but not so far: Britain's carbon intensity fell by 85 g/kWh in 2016, but its potential is close to exhaustion as coal is almost eliminated.

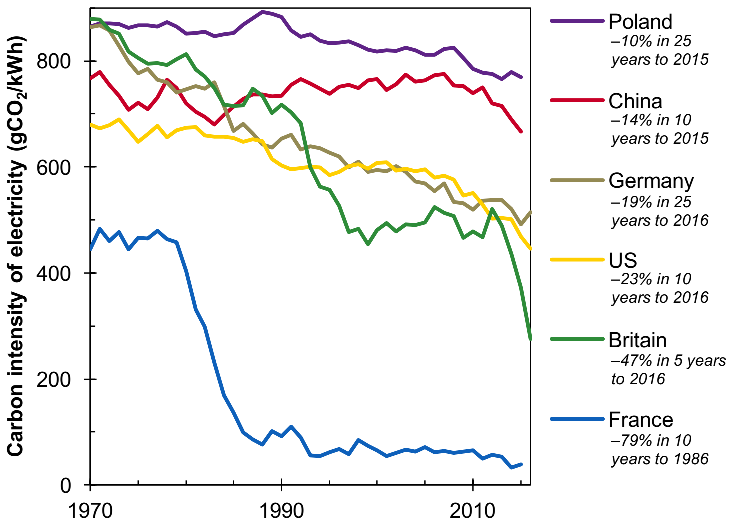

*Figure 1: **The carbon intensity of electricity generation in six countries over the last half-century.** Carbon intensity for gross electricity output (not accounting for losses in transmission and distribution). The legend indicates the depth and duration of sustained reductions in emissions intensity within each country. Data from refs.* 14,15.

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

Britain's power generation

Coal was the largest source of electricity generation for the first hundred years of Britain's power system. This changed in the early-1990s (Figure 2) when the newly-liberalised market invested in combined cycle gas turbines (CCGTs), for reasons unrelated to carbon mitigation[16].

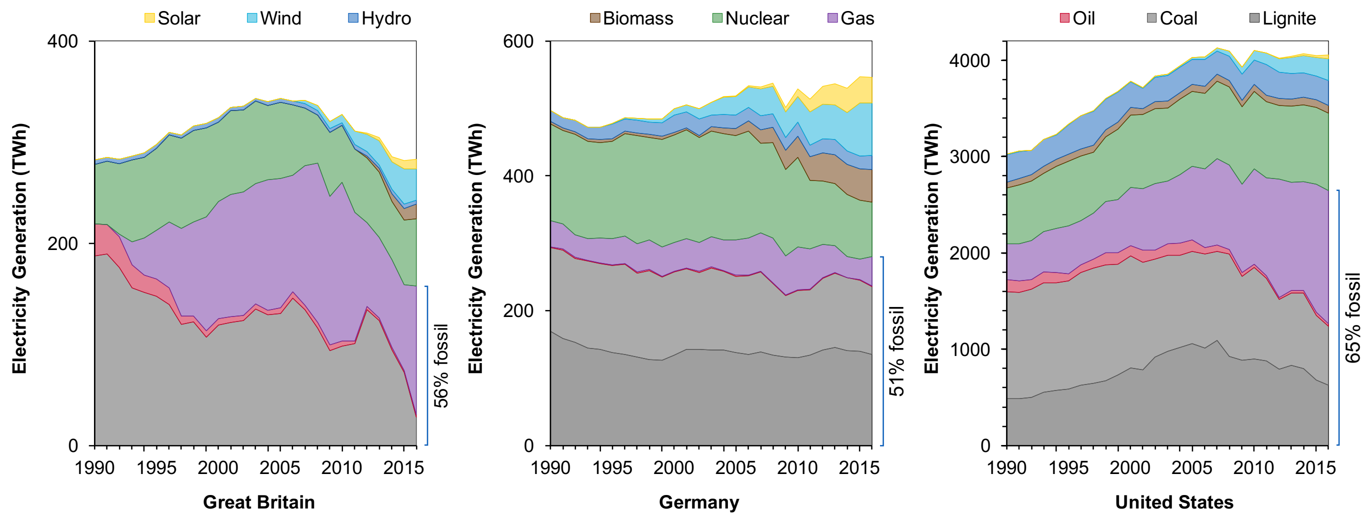

Figure 2: ***Electricity generation by fuel type in three countries over the last 25 years.*** *Imports are not included, waste is included with biomass. Between 2014 and 2016 coal + lignite generation fell by 5% in Germany, 22% in the US and 70% in Britain. Data from refs.* 17–20.

This 'dash-for-gas' in Britain was not replicated in Germany or elsewhere in Europe, and although termed a 'dash' it took eight years (1991–99) for new gas capacity to be built and halve coal's share of generation from 66% to 34%. Over the last decade, the US has shifted away from coal and lignite as shale gas production significantly reduced the price of natural gas. More recently, the combination of fuel switching and coal plant retirements in Britain has seen coal's generation share fall three-quarters to 9% in just four years (2012–16); helping to halve power sector emissions from 158 $MtCO_2$ in 2012 to 78 $MtCO_2$ in 2016. This fuel switch drove the largest ever annual reduction in British power sector CO_2 emissions[21] of 25 $MtCO_2$ in 2016.

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

If sustained, this rapid reduction arguably puts Britain well ahead of its near-term carbon reduction trajectory, as it could now beat its carbon targets for 2018-22 within the timeframe of the 2013-2017 carbon budget[24]. However, as power sector emissions are part of the EU Emissions Trading Scheme (referred to as the traded sector), the net UK carbon accounting[25] means that these reductions can be 'exported' from the power sector as a surplus to other parts of the traded sector (*e.g.* heavy industry) potentially in other countries in Europe. Under agreed carbon accounting rules, they cannot be allocated to, or purchased by the non-traded sectors in Britain (*e.g.* domestic transport or heat) to provide additional carbon headroom[26]. Nevertheless, the significant reduction in electricity carbon intensity provides a direct benefit for decarbonising these sectors through electric vehicles and heat.

Britain’s commitment to reduce coal power

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

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

Britain is therefore on track to become the first major economy to transition away from coal after centuries of production and consumption (Figure 3). The latter fell to 12 Mt in 2016[33], levels not seen since 1935[34]. The rate of this change is unprecedented; it took 14 years for power sector coal demand to increase from 12 to 28 million tonnes per annum (1936 to 1950), but only 1 year to make the reverse transition (2015 to 2016). Britain could be the first country to leave its coal reserves unburnt in the ground[35], and in November 2017 it set out a global alliance to end coal power generation[36]. This would have been inconceivable to policymakers even a generation ago, when coal, nuclear and oil generation powered the country[16].

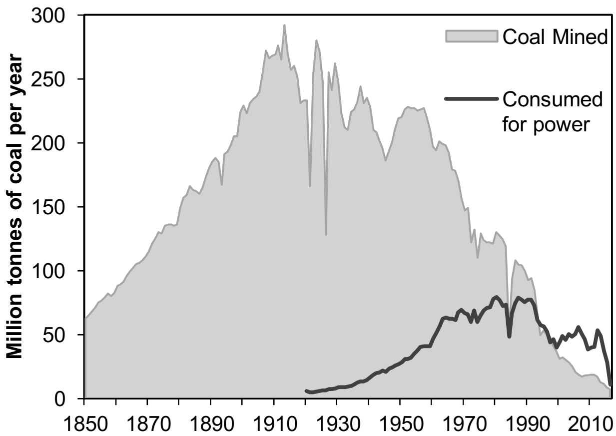

Figure 3: ***Quantity of coal mined and consumed for power generation in Britain.*** *Power sector data from ref.* [17] *and coal production data from refs.* 33 *and* 34.

[BOX 1 starts] Factors that enabled Britain's *rapid* fuel switch

Britain's experience of fuel switching can be viewed as a policy success, albeit at a rate that was better than anticipated. We suggest four factors were necessary to achieve this *rapid* fuel switch:

- Gas generation plants were already built and had spare underutilised capacity;
- Existing fuel supply infrastructure could cope with the increased power sector gas demand;
- The political will was available to intervene in markets to incentivise the switch, penalising coal vs. gas generation via an effective carbon price.
- Coal and gas prices were sufficiently close so that switching did not inflict large price rises on electricity consumers (a carbon price of £50/t was needed to incentivise fuel switching in 2013, vs. £16/t in 2016)[12].

Renewable generation has also rapidly increased in Britain, lowering emissions over the last decade, but contrasting Figure 2 and Figure *5*, significant reductions only occurred since the 2013 increase in carbon prices, due to falling coal emissions.

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

[BOX 1 ends]

Putting a price on carbon

Our view is that the primary driver for coal's substitution in 2015–16 was the higher price placed on carbon emissions. Since 2005 British power stations were subject to the EU Emissions Trading Scheme (ETS) but it delivered carbon prices that were too weak to drive sustained lower-carbon investment[40–43]. To address this, Britain introduced the Carbon Price Support (CPS) policy in 2013 which required power-sector emitters to pay a top-up price to a Carbon Price Floor (CPF) determined by policymakers[44]. This aims to provide generators with the certainty of a more stable (but higher) price of CO_2 than delivered by the EU-wide market alone.

This CPS policy is still subject to regulatory risk as the floor price can be changed. Its initial trajectory was rising towards £70/tCO_2 in 2030; however, successive announcements have frozen the CPF at its 2017 level of £18/tCO_2 at least until 2021. While this suggests diminished ambition in the face of cost sensitivities, it should be compared to an EU-ETS price of approximately €5/tCO_2 throughout 2016.

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

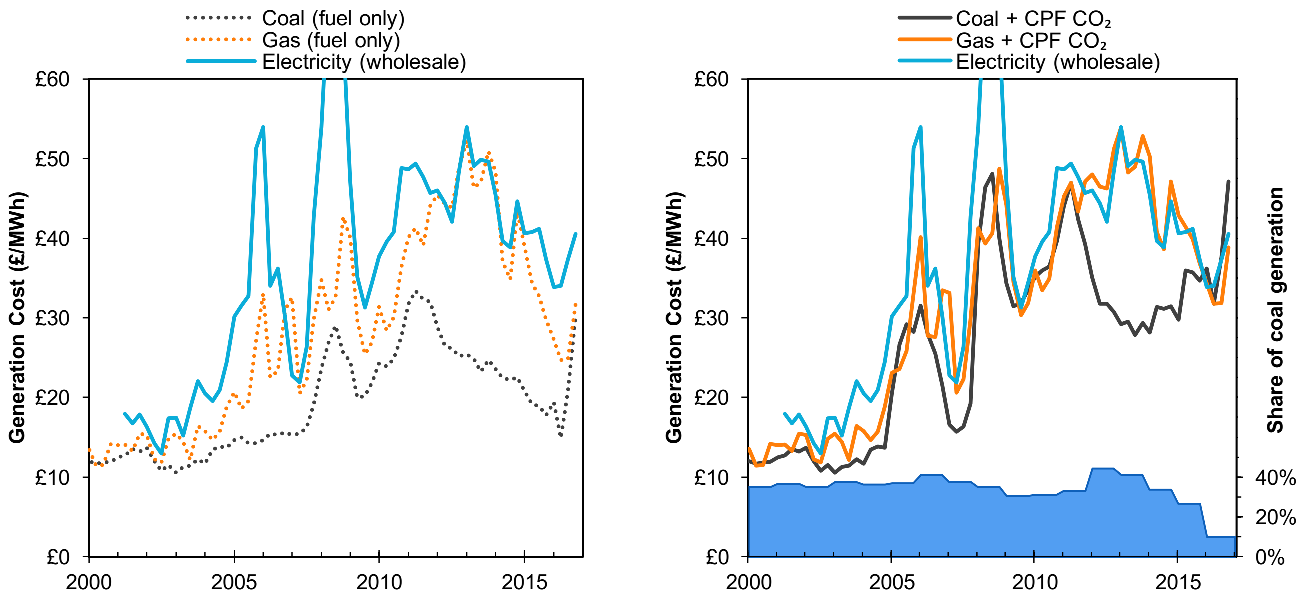

*Figure 4: **The wholesale price of electricity in Britain with the competitive benchmark based on fuel and carbon prices. a** electricity prices are compared with the estimated cost of generation from coal and gas with no carbon price. **b** shows the comparison including the prevailing carbon price in Britain, along with the share of total electricity generation from coal. Electricity prices are from the day-ahead spot market. Generation cost consists of fuel combusted (divided by conversion efficiency) and carbon emitted (multiplied by carbon price), neglecting other aspects such as maintenance and network charges. Prices and costs have quarterly resolution, the coal generation share has annual resolution. Carbon price data from refs.* 44 *and* 50 *, fuel price data from ref.* 51*, electricity price and coal share data from ref.* 12.

The costs of electricity generation are shown in Figure *4*, highlighting the falling cost of gas relative to coal since 2014. However, coal would still be the cheapest form of generation with the European ETS carbon price, despite the sharp rise in international coal prices through 2016 (due to China cutting production by 10%)[52]. Instead, the CPF allowed gas generation to become equivalent or cheaper since the beginning 2016 and displace coal's share of generation. In terms of historical precedence, the carbon price in Britain has been raised back to its level in 2008. In the rest of Europe, it remains at just one-third of its peak.

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

Leaving the markets to it

Britain's experience shows that liberal markets can rapidly adjust to well-timed well-aimed policy signals. Policy is not an essential ingredient though, as America demonstrates that a confluence of market factors can drive fuel switching alone, albeit at a slower pace.[53–55] Since 2005 natural gas prices have fallen 70% compared to 25% for coal due to increased production and the inability to export shale gas[5] (due to insufficient infrastructure). This has lowered the US average carbon intensity of electricity by a quarter (see Figure 1), with a 7% swing from coal to gas occurring in 2015, reducing power sector emissions by around 133 Mt[56].

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

Potential for fuel switching in Germany

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

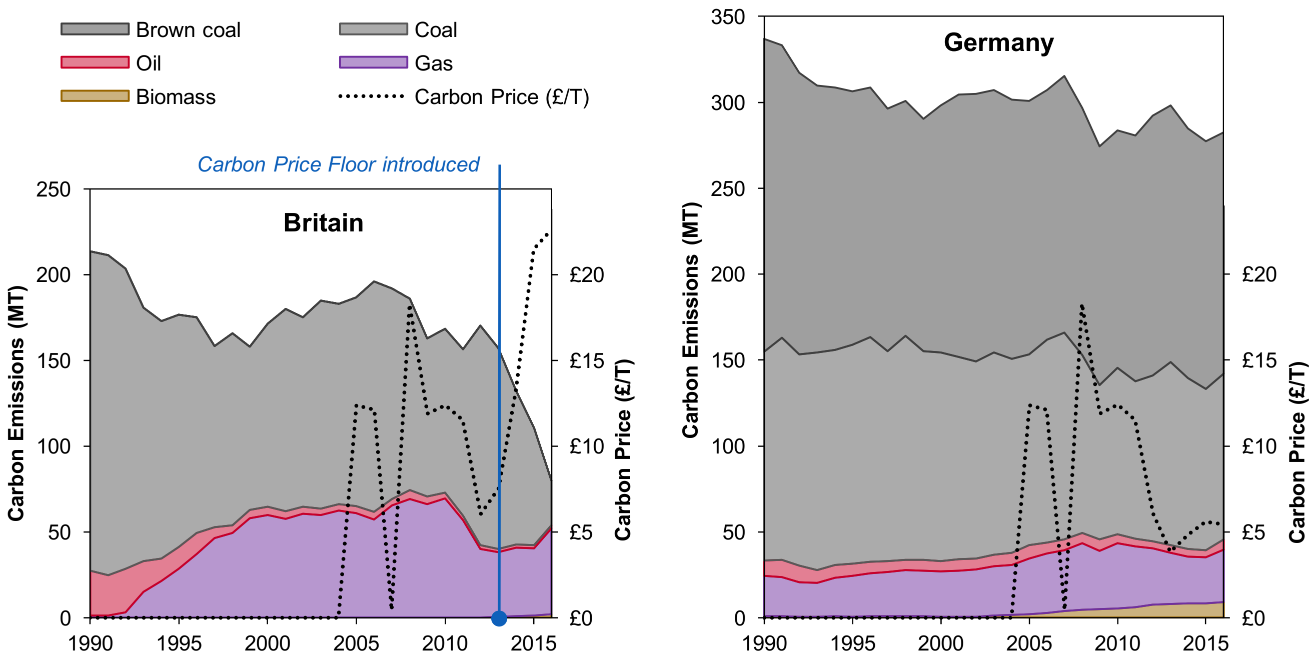

Figure 5: ***Power sector CO_2 emissions in Germany and Britain, broken down by fuel source.*** *The carbon price in each country is overlaid, showing the marked difference since the introduction of the UK's Carbon Price Floor in 2013. It is our view that this was the major additional factor that caused the rapid shift from coal to natural gas generation after 2013. data from refs.* 17 *and* 18*, emissions intensities from refs.* 32 *and* 12*, and carbon prices from refs.* 44 *and* 50.

Germany is self-sufficient for lignite but imports 89% of its hard coal[57], as its geology makes local production internationally uncompetitive. Import dependency for natural gas is similarly 90%, although only one-sixth of demand is from the power sector as gas is primarily used for heating[18]. Around 15bcm/year (~150 TWh/year) of spare capacity exists in the Nordstream pipeline for increased gas supplies[58], with an additional 55bcm/year (540 TWh/year) if Nordstream 2 is constructed. At a national level, it seems the fuel supply infrastructure has the potential to accommodate significant levels of fuel switching.

However, several reasons temper Germany's desire to take this route, not least the security implications of swapping indigenous lignite to imported natural gas. Germany's decision to remove nuclear generation provides an additional challenge: installing 60 GW of wind and solar power in the last decade has done little more than offset the lost output from the 10 GW of retired nuclear power[32]. Both considerations were not applicable to Britain, which has no lignite mines, and in contrast to Germany, is embracing new nuclear build. Germany is a fascinating interaction of political economy interests, with a lignite lobby that capitalises on security of supply and cost arguments for Germany's energy transition. However, without the development of Carbon Capture and Storage in Germany (which currently seems highly challenging) at some point lignite generation will be impossible to reconcile with decarbonisation targets, and Britain's experience shows this could be rapidly reduced given Germany's pre-built but underutilised gas generation capacity.

Germany has 24 GW of gas-fired power stations, compared to 28 GW of hard coal and 21 GW of lignite[32]. In recent years, nearly-new gas power stations have been mothballed after proving unprofitable, and eventually exported to the Middle East[59]. This is because gas capacity lies mostly unused, with 18% utilisation vs. 40% for hard coal and 74% for lignite in 2016[18]. An additional 155 TWh of electricity could be produced if this gas generation capacity were utilised at 80%, sufficient to completely eliminate hard coal plus four-tenths of lignite production, which would cut Germany's power sector emissions by around a quarter, or 62 $MtCO_2$ per year.

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

Potential for fuel switching globally

Quantifying an accurate global potential for fuel switching requires a detailed country-by-country analysis of infrastructure, generation and demand, prices and policies. Nonetheless, the broad order-of-magnitude can be estimated using statistics for annual generation and installed generating capacity. We estimate the potential for fuel switching in the 30 largest coal consuming nations (covering 97% of global coal capacity) by compiling the amount of coal and lignite generation in 2015, and comparing this to the additional generation that could come from gas in each country. This is based on existing, underutilised gas generation; disregarding the option of building new capacity. The maximum gas generation potential assumes that combined-cycle gas turbines (CCGTs) could run up to 80% utilisation (limited by availability and downtime), while open-cycle (OCGTs) and steam boiler stations would be limited to 0–40% utilisation (due to economic rationale). Displacing coal with single-cycle (rather than combined-cycle) gas stations would yield half the carbon savings due to their lower efficiency and thus higher carbon intensity. We assume CO_2 emissions of 405 g/kWh for CCGTs and 710 g/kWh for OCGTs, relative to 1025±55 g/kWh for national coal fleets[14]. Sources, details and justification are given as supplementary information.

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

Poland depends on solid fuels for over 90% of its electricity, and lacks the pre-existing gas plants to take over market share[60]. Japan is still gripped by a capacity shortage in the wake of the Fukushima disaster and shutdown of its nuclear fleet, thus its gas stations are running close to capacity already.

Figure 6b shows that if fuel switching was fully realised in these 30 countries, annual emissions could fall by 0.8–1.2 $GtCO_2$, around 3% of global emissions. Reductions in China, India and Europe amount to 440 $MtCO_2$ per year, and are insensitive to the utilisation of single-cycle plants as these make up only a fifth of their gas fleet. The mitigation potential in the US and Russia is more sensitive to the assumed utilisation, as OCGTs and steam boilers form half their gas capacity.

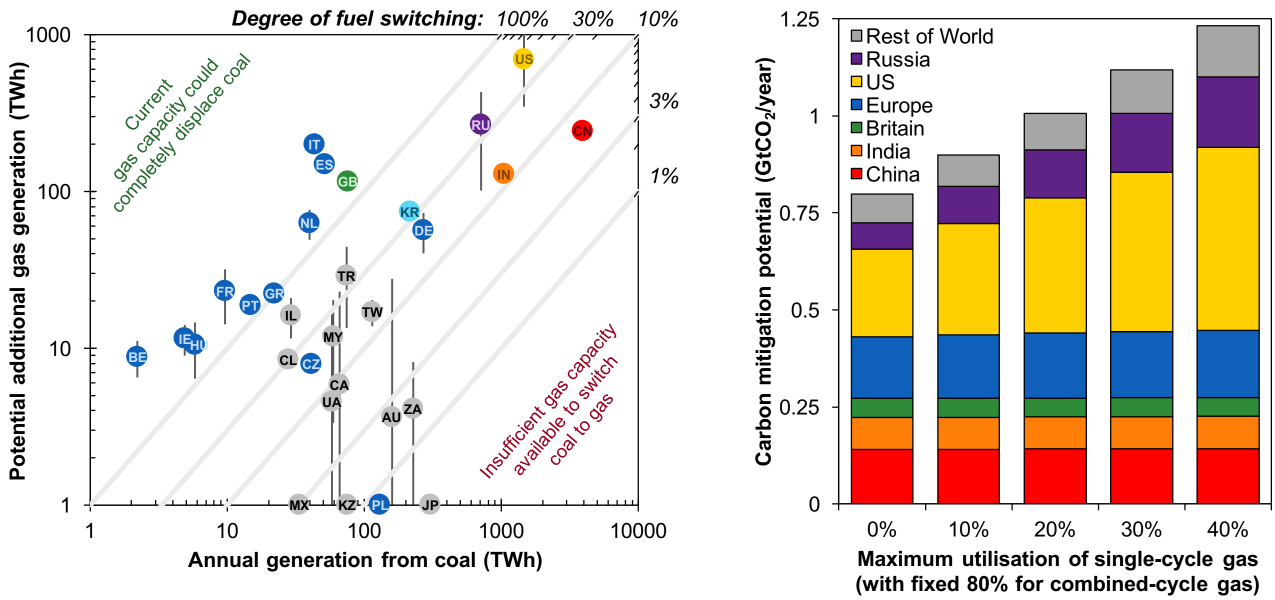

Figure 6: Estimation of the carbon mitigation potential from fuel switching in 30 countries. ***a*** *Comparison of output from coal power stations in 2015 with the potential for additional gas generation, if existing combined-cycle gas plants operated at 80% utilisation and single-cycle plants at 20%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

No Silver Bullet

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

Fuel switching will change supply-chain and energy security risks, and in many countries would create political tensions by increasing import dependency for primary energy. Although employment in the coal sector has fallen dramatically in many western countries, policies which are seen to further decimate domestic mining industries will face opposition, as seen in America. Over the longer term, politicians must grapple with the consequences of transitioning away from solid fuels; notably how to engage and retrain affected mining communities where coal production is culturally significant, as well as a source of employment.

There are also risks with carbon leakage in highly interconnected markets such as Germany[61,62]. A strong carbon price to promote fuel switching can reduce within-country emissions, but may also shift electricity production (and thus carbon emissions) to areas subject to a lower carbon price. Britain now imports high-carbon electricity from the Netherlands, where coal usage increased 40% and generators pay one-fifth the carbon price. Supranational harmonisation of carbon pricing is needed to avoid the 'offshoring' of power sector emissions. Other considerations, such as the level of methane leakage in the natural gas supply chain must also be carefully assessed[63,64].

Carbon pricing however is not a blanket policy that will work everywhere. In countries which lack the gas infrastructure such as Poland or Japan, raising a carbon price would in the short term be no less blunt than a blanket tax on electricity. In the longer term, a careful balance is needed to redirect how existing infrastructure could be used without going so far as to incentivise building new gas infrastructure and avoidable carbon lock-in. If no more carbon emitting electricity generation can be built for a 2°C temperature rise to remain likely[65], the distinction between utilising existing gas generation versus investing in additional capacity is of critical importance[66,67].

Conclusions

Switching between fossil fuels can only ever be a temporary stepping stone. Its potential is bounded by the scale of existing coal and gas infrastructure, and natural gas is incompatible with deep decarbonisation[68,69] unless carbon capture and storage emerges from its 'valley of death'[10]. If spare capacity already exists, then fuel switching does not require several years to wind up to material emissions savings, unlike other key options (renewables, nuclear, efficiency improvements). The 'quick win' is provided simply by using pre-existing infrastructure more effectively.

Britain's example highlights the effectiveness under certain key circumstances of placing a modest, but stable, £18/tCO2 on carbon, and the speed with which the power sector generation changed in response to such a signal; it switched 15% of its generation mix (45 TWh) in a single year, saving 25 $MtCO_2$. Fuel switching can demonstrably achieve very rapid carbon reductions. In comparison renewables took six years to grow from 4% to 19% of Britain's generation (a 45 TWh/yr increase), saving approximately[12] 22 $MtCO_2$. It will be at least 10 years before new nuclear capacity will be built in Britain[59], which would require three projects the size of Hinkley Point C to save 27 $MtCO_2$ per year[70] to fuel switch from natural gas (as coal will no longer be on the system).

Fuel switching can also be a cost-effective and convenient form of decarbonisation. If driven solely by market forces it will lower bills; if policy support alters the balance between closely-priced fuels, it can have minimal impact on consumers, as seen in Britain. Natural gas retains the energy system benefits of being a fuel: controllable and dispatchable generation, and extensive storage infrastructure with days to weeks of capacity, rather than minutes to hours for electrochemical and thermal storage[71,72]. Controllable flexibility is increasingly desirable to accommodate greater levels of variable renewable energy generation, especially so if coal generation is simultaneously being retired.

Anthropogenic carbon emissions had almost plateaued[73]. The next, momentous step, for emissions to decrease, could be catalysed by a concerted global effort to switch away from coal to natural gas. Our initial examination suggests the top 30 coal consuming countries could prevent 1 GT of CO_2 emissions from entering the atmosphere annually; with a central estimate that 20% of the world's coal could be switched to gas using existing, under-utilised infrastructure (the range is 13% with no OCGT up to 27% with them running at 40% utilisation). This provides an immediate benefit to slow the increase in cumulative carbon emissions, buying all-important time for other sectors to catch up, and providing cleaner electricity with which to decarbonise them. Any effort to front-load emissions reductions will ease the pressure on future generations who are faced with removing emissions back out of the atmosphere[74]. However, it is vital to cumulative emissions that the gains of early decarbonisation from fuel switching are not squandered by the extended use of gas generation as a substitute for the necessary increase in low-carbon technologies.

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

Acknowledgements

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