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The future of fossil fuels – is it the end?

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Abstract

Contrary to the assumptions underlying much of current energy and climate policies, fossil fuels have fallen and may remain at the new "normal" levels. In the medium term, Iran and Iraq have considerable potential to increase their outputs, and the new shale technologies will gradually globalise. Longer term, new technologies in electricity generation, storage and smart demand side technologies, together with electric cars and the shift towards digitalisation and new electricity-based technologies in manufacturing, with increase demand for electricity, but not fossil fuels. These new and emerging technologies, rather than international agreements, and the promotion of current generation renewables, will probably bring fossil fuel dominance to a gradual close. To facilitate decarbonisation, energy policy should be directed at enhancing R&D and next generation renewables, instead of supporting existing ones.

JEL classification: Q4, L9, O3.

1.Introduction

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The demise of fossil fuels has been often predicted, but they have proved remarkably resilient. Stanley William Jevons in the nineteenth century worried that Britain was running out of coal, and would as a result have to return "to her former littleness"[2]. Yet nobody worries that the world is going to run out of coal a century and a half later. For oil, the end has been predicted in almost every decade since the modern oil industry was founded. Gas started out as a premium fuel, so precious that both the US and Europe banned its burning for electricity generation until 1990. Yet now it appears to be superabundant.

Recent claims about "peak oil" have turned out to be ill founded, though they were believed by the majority of policy makers from the 1970s right up to the end of 2014[3]. Indeed, so convinced have politicians and policy makers been, that fossil fuel prices would go ever upwards, that they were confident that investments in current renewables, like wind, and solar, would require only temporary subsidies, and by around 2020 Europe's renewables industry would give it a competitive advantage over the predicted much more expensive fossil fuels the US would still be dependent upon.[4]

Recent events have confirmed the errors of the peak oil theorists and their policy followers. In less than a decade, shale oil and gas developments have transformed the US's oil and gas production, adding over 3 million barrels a day (mbd) to its oil production and creating the possibility that North America might become energy independent in the 2020s. By the end of 2015 oil prices had fallen more than 60% since late 2014, following an earlier sharp fall in coal prices, and now complemented by gas price falls too. Abundant cheap fossil fuels are back.

Yet another century dominated by fossil fuels would probably be disastrous. It is the fossil fuels that are responsible for the bulk of the increase in carbon emissions, and it is trivial to show the incompatibility of the projected increases

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[2] Jevons, W. S., (2008 edition), p.236.

[3] Helm, D.R., (2015a, chapter 7).
[4] See Helm, D.R. (2015a), chapter 4.

in oil, gas and coal demand and the 2 degrees warming limit scientists recommend. Decarbonisation is not compatible with this continued fossil fuel growth.

All however may not be lost from a decarbonisation perspective. Governments could force decarbonisation, by adopting policies which push fossil fuels out of the energy mix: by, for example, putting a price on carbon; imposing command-and-control rules, like emissions standards; and mandating Carbon Capture and Storage (CCS). But, so far, the evidence is that existing policies are not likely to bridge the gap.

Nothing of substance has been achieved in the last quarter of a century despite all the efforts and political capital that has been applied. The Paris Agreement follows on from Kyoto. The pledges – in the unlikely event they are met – will not meet the 2C target, shipping and aviation are excluded, and the key developing countries (China and India) are not committed to capping their emission for at least another decade and a half (or longer in India's case)

But if decarbonisation policies are not working at anything like the required scale, and if they are unlikely to do so for the foreseeable future, there is only one other alternative - new low carbon technologies which can compete head-on with fossil fuels. Here there is great scope for optimism, as we shall see.

The structure of this paper is as follows. Section two looks at current fossil fuel markets and current projections. It provides the base case – one in which fossil fuels resources are abundant, and prices remain low now that the commodity super cycle is emphatically over. Section three looks at decarbonisation policy in this low price scenario, and explains why current efforts are pathetically inadequate in the context of the climate change challenge. Section four turns to new technologies and explains the grounds for optimism. Section five considers the appropriate policies to support the new technologies, and contrasts these with the inefficiencies of current attempts to "pick winners", in particular wind and current generation solar. Finally, section six concludes.

2. The end of the commodity super cycle – abundant cheap fossil fuels

The most widespread prediction of the end of oil is that advanced by the peak oil theorists. The claim is remarkably simplistic, and derives in its modern form from the work of Hubbert (Hubbert 1956). He assumed that the major US discoveries had all been made, and hence the resource base was known. He assumed a maximum depletion rate for the existing wells, and predicted on this basis that US oil production would peak at around 1970, and decline thereafter.

Hubbert got his prediction right. Within the confines of a US supply side argument, he simply extrapolated on the basis of his assumptions. US oil production did peak in 1970. But it did not then follow the path of inevitable decline Hubbert also predicted. It turned out that his two assumptions were only temporarily correct – the resource base turned out to be much bigger once shale is included; and depletion rates are a function of cost and technology, and can be increased. With the price rises in the 2000s, there would be a shale oil and gas revolution in the US.

Hubbert's mistakes were trivial compared with those made by his followers. They claimed that the US database proved a template *for the world* [5]. Furthermore they added demand, and extrapolated this out too. If it assumed that the world's major oil resources have all been found, and a assumed depletion rate is applied to these known oil fields, and the projected supply is compared with the assumed growth in demand, it is merely a matter of predicting when the peak will be reached. At and beyond that peak, prices will increase sharply (since the demand is assumed to be inelastic) and the sorts of economic shocks that the OPEC price increases in the 1970s delivered to the world's economy will be repeated. In this peak oil world, economic growth as we know it will grind to a halt unless alternative technologies come to the rescue.

[5] See for example Campbell, C. & Laherrere, J (1998).

In the period since 2000 it is not hard to see why the peak oil idea gained policy traction. Prices started to rise from a low of less that $10 a barrel to peak at over $140, punctuated by a short lived and sharp fall in the immediate aftermath of the financial crisis in 2008, and then remained in the range of $100-$110 for the five year period up to the end of 2014. Behind these price increases lay the growth of China, with its economy doubling every 7 to 10 years, driven by fossil fuels. Extrapolating out Chinese income per head, and assuming an income level at which car ownership kicks in, it is easy to project a great surge in the demand for oil for transport. Furthermore, even if China started to tackle urban pollution, the total coal burn to underpin the electricity industry (and other energy intensive industries like steel) would go ever upwards.

The China effect on fossil fuel demand (and other commodities) has indeed been extraordinary. China was a net exporter of coal until the mid 1990s. By 2014, it accounted for half of all world coal trade.[6] China has now become one of the largest importers of oil, and it is beginning to build up its gas imports too. For all its investments in nuclear, solar and especially hydro, China's economic rise is largely a story about a surge in fossil fuel burning. Adding in the damage to its rivers and soils, China's rise has been an environmental disaster[7].

Almost all that could be wrong about the peak oil narrative is wrong. The world's fossil fuel resources are abundant. The earth's crust is riddled with fossil fuels. The shale revolution merely adds to the large-scale conventional resources yet to be explored and exploited. Technological progress has transformed what can be accessed and extracted – from US shale, to Canadian tar sands, to the enormous potential of the Arctic and other offshore opportunities. Peak oilers assume technology is given. Yet in the fossil fuels, the frontiers are being continuously expanded in what is a giant field experiment carried out daily across a host of oil fields and drilling sites. The fact that the shale revolution took less than ten years to transform the US, and with it world energy markets, is an example of the scale, speed and impact of innovation in the fossil fuel industries.

[6] See Heckler in this issue for a coal perspective. See also IEA (2015).
[7] The building on reefs in the South China Sea is yet another example.

There is no serious physical resource constraint. There are however political and economic constraints. The costs for oil production vary a great deal – from perhaps as low as $5 a barrel in Iraq and Saudi Arabia, to over $90 in the offshore Arctic. In a rational market, the cheapest reserves would be depleted first, and the more expensive marginal supplies would be brought on later – after the core Middle Eastern oil fields had been exhausted.

That indeed is what happened for much of the history of the oil industry, up to the 1970s. The oil price remained remarkably low and stable for decades, and production was located in the cheap places – Venezuela, the US, Russia, Iran, Saudi Arabia, Kuwait and Iraq. The OPEC oil shocks of the 1970s changed all this. Once the Arabs imposed an embargo, the security dimension rose up the political agenda, whilst the higher prices made Alaska and then the North Sea profitable. Once these marginal reserves had come on stream, they stayed. When the prices increased after 2000, the search for more marginal resources gathered pace. There was US shale, Canadian tar sands, Angola, Brazil, East Africa, Sudan, and Congo amongst others all adding to global supply.

In the dance between OPEC with its low costs on the one hand, and the development of marginal resources as prices increased on the other, Saudi Arabia plays a pivotal role. It has abundant cheap resources, and it *had* swing production. Its actions made the first oil shock in 1973 stick, and its failure to accommodate the impact of the Iranian revolution in 1979 allowed prices to rise to a peak of $39 a barrel – a level only briefly touched in the subsequent 35 years. As the 1979 shock took its toll on the world's economy, demand fell back, whilst the new marginal resources were developed. Demand went down and supply went up in response to the increase in prices – which was expected to be permanent.

Saudi Arabia (and the other OPEC members) reaped what it had sown[8]. By the early 1980s, its production had fallen back very sharply, way beyond its potential of over 10 mbd as it lost market share. By the mid-1980s it had had enough, particularly as Iran – which had become its great regional rival – started to gain ground against Iraq in the Iran-Iraq war (1980-88). It decided to win back market share by increasing output. The result was a sharp fall in oil prices, to recover only briefly with the first Gulf War, eventually bottoming out with a low of $9 a barrel in 2000. After 2000, the Chinese demand growth began to bite, whilst low prices had deterred marginal supplies. Low prices reduced supply and increased demand. The market tightened and prices started to go up.

By late 2014, the growth of US shale had worked its magic on global markets. The US oil production surged up by around 3 mbd a day towards 10 mbd, and with its gas it became again the world's largest producer of oil and gas. Saudi Arabia then repeated its mid 1980s strategy, again in part motivated by the threat from Iran, as sanctions began to be lifted. It decided it would try to hold onto market share. It increased its production too. Supply therefore flooded the global oil market, and coincidentally China's great economic growth began to falter. The commodity super cycle, which China had been the proximate cause of, came to a shuddering halt. Price had again done its job: supply increased and demand fell.

It might be thought that having worked so effectively in bringing supply and demand into balance, the Saudi strategy would cause prices to rise again after a short lag, once the current low prices have choked off marginal supplies, caused sharp falls in exploration and increased demand. This however may be a mistake: this time it may well be different, and for four reasons.

First, the impact of the shale may have changed the global game and changed fundamental assumptions. As the costs fall sharply around the world, the new technologies for horizontal drilling, fracking and seismic information could open

[8] See Fattouh & Sen in this issue for an analysis of Saudi Arabian and OPEC strategy.

up a cornucopia of deposits around the world, from Argentina, to Algeria and China, as well as in all the existing conventional locations. The new techniques could increase depletion rates of existing conventional wells too. Whilst low prices are a set back, the multiple technological advances cannot be un-invented.

Second, the key oil producers now have much more pressing revenue requirements than at any time since the 1970s [9]. Venezuela, Russia and even Saudi Arabia need an oil price of over $90 a barrel to balance their budgets. They have increased their expenditures as oil revenues rose in the last 15 years, and most recently in the Arab world to buy off the threat from the Arab Spring. With much higher populations, growing rapidly and with a young age profile, sharp expenditure cuts are politically dangerous for the ruling elites. Even Saudi Arabia has had to return to the international bond markets and its reserves probably cannot stand more than about three years of prices at even $40-$60 a barrel. The response has therefore been to *increase supply* in the face of the price falls. With the prospect of Iran returning to the market, and Iraq pushing up its production, and whilst China continues to slow, the chances of a sustained OPEC-led set of production cuts to raise prices is limited. To this can be added the sharp fall in US shale costs. These costs turn out to be endogenous to the oil price – labour, materials and rig costs have all have fallen in response to the fall in the oil price, and US production continued to rise throughout 2015.

The third and fourth reasons why the price may not recover are the subject of the next two sections – the impact of decarbonisation; and of new low carbon technologies.

3. Decarbonisation policies and why they have failed to make much difference so far

Peak oil can be dismissed as a serious argument. The combination of the shale revolution and the ending of the commodity super cycle probably point to a period of low prices for sometime to come. This is unfortunate timing for current

[9] See Rick van de Ploeg in this issue.

decarbonisation policies, many of which are predicated on precisely the opposite happening – high and rising prices, rendering current renewables economic. Low oil prices, cheap coal, and falling gas prices, and their impacts on driving down wholesale electricity prices, are the new baseline against which to consider policy interventions.

The confounding of expectations has an historical parallel. At the end of the 1970s, it was assumed that oil prices would go ever upwards, and the power of OPEC would grow. The US under Carter's presidency opted initially for solar and nuclear. Carter even had solar panels installed on the White House roof. Europe decided nuclear was the answer. France pushed through its massive nuclear programme (at one stage building 6 nuclear power stations simultaneously), and Britain announced in 1981 that it would build 10 new PWRs – one per year [Helm (2004 chapter 5)]. Germany, Italy, Switzerland and Belgium followed suit. Japan, like France, aimed for over 50 reactors. Canada added another 10. Most countries boosted indigenous coal too.

All of this was based upon the widespread belief at the end of the 1970s that the 1980s and 1990s would see a further doubling of oil prices. When this failed to materialise, the great hopes for nuclear and solar fell away, exacerbated in the US by the Three Mile Island nuclear accident. Only France and Japan seriously persevered, and each for their own particular historical, strategic and security reasons. (In France's case, nuclear was a military as well as civil imperative). [10]

This time around, the fall in oil prices has been accompanied by cheap and abundant gas as well as coal. Shale gas has effectively killed off new nuclear in the US. Coal and gas prices have driven down wholesale electricity prices across Europe. In Germany, Fukushima accelerated its exit from nuclear, but the economics of new nuclear have in any case been radically changed, from an assumption of rising prices to a world of falling prices.

[10] See Leveque (2015) chapter 10.

As recently as 2014, the British government forecast that the wholesale electricity price would keep on rising throughout the next decade.[11] Thus when the first of a planned new set of nuclear power stations comes on stream, it would be competitive against the assumed higher wholesale electricity price. The developers of Hinkley, the first project, were therefore awarded a 35-year contract at £92 mWh safe in the assumption that there would be no subsidy. It is however, already apparent that £40 mWh may be a better benchmark and, as we shall see in section 4 below, there are good reasons to expect low marginal cost renewables to drive it even lower later in the 2020s.

Current generation renewables and nuclear are therefore likely to be out of the market for a sustained period, and hence the subsidies that were supposed to wither away after 2020 are likely to be permanent[12]. To be cost competitive, something more is needed on the technological side to bridge the gap with fossil fuel prices.

The obvious policy response to falling fossil fuel prices is to raise the price of carbon. Setting carbon prices inversely to the oil price has two rationales – a substitution and an income effect. Oil prices already include an implicit carbon price, augmented by the implicit carbon elements in the plethora of existing fossil fuel taxes. If the marginal cost of oil is say $2-$5 barrel, and the price is $50, then the implicit tax element (the economic rent) is $45 or more. Add to this the taxes on petrol and diesel and the total is even higher. In other words, existing monopoly rents and energy taxes are imperfect proxies for carbon taxes, since oil (and the other fossil fuels) is primarily carbon. The popular argument that the fossil fuels prices are in fact subsidised assumes that the marginal cost of oil (for example) is equal to the world price, and then falls into the trap of

[11] For DECC's annual forecasts see https://www.gov.uk/government/collections/energy-and-emissions-projections.

[12] For an analysis of electricity markets see Green & S. in this issue.

extrapolating high oil prices into the future.[13] The much quoted IMF study (Coady et al 2015) does this and then adds in a plethora of externalities and also a general consumption tax in a partial equilibrium framework (and neglects therefore the fact that all the other prices in the economy are distorted). The result is a pre-tax global subsidy of $500 billion and a post tax subsidy of $2 trillion. These estimates are open to serious challenge on all the key assumptions, but even if the methodology is accepted, the 50%+ falls in world oil prices since late 2014 and the halving of coal prices would significantly reduce the pre and post tax numbers (because the consumption tax is a percentage of the assumed pre tax subsidy). This however has not stopped the headline numbers being very widely quoted by world leaders and campaigners.

The substitution effect is the one that is necessary for decarbonisation. The aim here is to set a carbon price for the long term, which is stable and gradually rising through time. This creates the expectations that underpin deployment now of low carbon technologies and substitutions to lower carbon fossil fuels (coal-to-gas), the deployment of new technologies, and research and development into the next generation of energy sources.

Current proposals for carbon pricing revolve around emissions trading schemes, with the EUETS the lead example. This approach has been preferred to explicit carbon taxes, following on from the interests of the polluters in having the permits grandfathered, and those of financial institutions interested in exploiting the trading opportunities. So far the results have indeed suited the polluters and traders. The price of carbon in the EUETS has been very short term, very low and volatile – indeed so low that it is hard to identify any investment decisions that have been affected by it[14]. Indeed so disappointing has the EUETS proved that the European Commission is to intervene to try to doctor the number of permits to produce a higher price, thereby undermining the core feature of the scheme:

[13] It is very hard to work out form the published paper what the assumed future oil projections are, and why the link to retail prices is dampened.
[14] See for example Teyssen, CEO of E.ON, quoted in Helm (2015a) p.189.

that the permits are fixed so that the market reveals the price.[15] Now the number of permits is to be varied to target an implicit pre-determined price. Whilst the pure permits approach has some merits, the evolving hybrid is significantly worse that either a permits scheme or a tax. Making matters even worse, a number of countries have introduced carbon taxes and floor prices on top of the EUETS – *fixing the price and the quantity.*

The immediate potential effect of a carbon price lies less with the low carbon renewables and more with the relative pollution from the different kinds of fossil fuels. The obvious way to reduce short-term emissions is to switch from coal to gas. Coal has roughly twice the carbon emissions of gas, and coal's full cycle is worse that gas in respect of methane leakage, nitrogen oxides (NOx) and sulphur oxides (SOx), transport costs, and water pollution. Even fracked gas pales into environmental insignificance compared to coal mining and coal burning.

The very low EUETS carbon prices have so far had no noticeable impact on this substitution. Indeed in Europe, and particularly Germany and Britain, the substitution has if anything gone the other way – from gas to coal. There are two reasons for this retrograde step. Coal prices have fallen more sharply and earlier than gas prices, as a result of the slow down in China and the surplus US coal, as the US has switched to gas from coal. But in addition, the EU's renewables policies have been set independently of the electricity wholesale markets and the EUETS. Hence reductions in emissions due to renewables create more headroom within the EUETS, and therefore more room to expand coal (and this works by holding down the price of carbon). The result is that the renewables gains from a carbon perspective have been almost exactly offset by an increase in the coal burn – especially in Germany. Add in the emissions from the lignite coal mining which has been expanding in recent years in Germany, and the outcomes are retrograde in respect of addressing climate change[16].

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[15] See for the details
http://ec.europa.eu/clima/policies/ets/reform/index_en.htm
[16] Germany is as a result unlikely to meet its domestic 2020 carbon target.

The inefficiency of the EUETS is compounded by the inefficiencies of the support mechanisms for renewables. Although the coal-to-gas substitution opportunities have not been taken, the support for the renewables has been substantial, as the 2020 EU Renewables Directive has driven investment. Whilst there are strong arguments for supporting the R&D and the innovations necessary to bring renewables technologies to maturity, these are *separate* market failures from the carbon problems, and require *separate* policy instruments. The costs of the renewables support mechanisms should be compared with the carbon price that would have induced the same carbon emission reductions.

There are good theoretical arguments for preferring a carbon tax over an emissions trading scheme[17]. But there is a practical one too: carbon taxes can be flexible, whereas permits schemes need to be fixed for a considerable period. Consider the current low fossil fuel prices. This is a moment to raise the price of carbon – to offset the fall in the implicit carbon price embedded in oil and gas prices; to head off the rise in demand through the substitution effect; and because of the income effect. Given that energy demand is inelastic in the short run, this income effect is likely to be large. But it also means that households can afford to spend more on tackling climate change. For any given budget, the carbon price can rise inversely to the oil price falls.

In the absence of the adjustment in the carbon price, the fall in oil prices at the end of the commodity super cycle is likely to induce a rise in demand and might create the next cycle. For some, this underpins their confidence that the price will eventually rise, rendering the current renewables economic. The problem is that even if this is true (which it probably is not as we shall see in the next section below) there is not time to wait. Last time around it took nearly 15 years for the price of oil to respond (between 1986 and 2000). On the current business-as-usual emissions path to 2030, the result will be that the 2 degrees target is missed.

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[17] See Hepburn (2016) for a summary of the main arguments.

Further ahead, the carbon issue is likely to gain greater policy traction. The forecasts of oil, gas and coal demand presented by the major oil companies are obviously not compatible with the overall targets. There is a total envelop of possible emissions – a total carbon budget consistent with the 2C limit. Rather than take a forecast, we can take a determined maximum path for fossil fuel emissions. This path is not certain: substitution between fuels, and particularly coal-to-gas, and oil-to-gas impacts on the total; non-energy emissions will need to be taken into account; and new science will refine our understanding of the relation between emissions and temperatures. But the broad parameters are known[18].

With existing technologies, it is a matter of political will, and the ability to bring the main polluters on board, as to whether the envelope will be breached. There are good reasons to doubt that any top down agreement will work sufficiently well to achieve it. In the Paris Agreement, the leading polluters' pledges are in aggregate well outside the envelope. China's position is that it will start to reduce emission after 2030 – after another 15 years of potential growth. Were the economy to continue to expand on its current path, it would be more than twice its current size by them[19]. Its emissions would not have doubled, as it is reducing the share of coal in its energy mix, but they would nevertheless be substantially higher. Fortunately, from a climate perspective, there are many reasons to expect its growth path will be lower. India, another coal-based economy, plans to go on increasing emissions for decades to come. None of the pledges is, in any event, legally binding. For this reason, the Paris Agreement can be regarded as the point at which the UN negotiating approach turned effectively away from a top down approach, and instead started to rely on a more country driven and hence bottom up one.

Thus for an oil producer or an oil company, if the goal of containing and reducing emissions lies with Paris-type agreements, future demand growth is reasonably

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[18] See Myles Allen in this issue.

[19] China's emissions are at best estimates. Recently the total coal burn was revised upwards by 17%.

assured. It will take a change in technology to bridge the gap, and, as we shall now see, there are lots of possibilities.

4. New technologies – the grounds for optimism

The end of the super cycle probably means lower oil, gas and coal prices for sometime to come. It will take perhaps a decade for the demand to rise and the supply fall sufficiently to create another boom in prices – if ever. Current decarbonisation policies will not, in themselves, spell the end for fossil fuels. But what might, are alternative technologies. The age of oil, gas and coal will almost certainly not come to an end because we run out of these fuels. There is more than enough to fry the planet many times over. It will end – if it does – because there are better alternatives.

It is impossible to know in advance what technologies will be successful. It is in the nature of technical progress that there will be surprises. If we had the knowledge to predict, we would have the technologies already. But we are not entirely ignorant. Some at least of the surprises are predictable in outline, and indeed some come from the combination of developments already known.

In thinking about a post fossil-fuel world, it is a common mistake to equate this with a world that uses less energy: hence the familiar error in policy making of trying to reduce the demand for energy (and the even bigger mistake of thinking that increasing energy efficiency reduces the demand for energy). On the contrary, there is no shortage of energy, and no shortage of non-fossil fuel energy to draw upon. The sun comes up everyday: there is more energy transferred to the earth from the sun every hour than the entire world's electricity demand for a year.

In capturing this energy (and other non-fossil sources like geothermal, gravity (hydro) and nuclear), the main vector is likely to be electricity. It is growing as a share of final energy consumption, and there are good reasons to expect this trend to continue. Information technologies favour an electricity world, the electrification of transport points away from oil, new materials like graphene are more electricity friendly, and robotics and 3D printing are electricity driven. The internet-of-things is increasingly supported by the electrification-of-everything.

So the main focus should be on electricity. Technical change is taking place at all stages of the electricity vertical chain – from generation, to storage and batteries, through to the way energy is consumed, and the new materials and production processes which lie behind the industrial demand for electricity.

Electricity generation is essentially a process of converting multiple different sources of energy into electricity. The dominant one for the last century has been coal, with some contribution from nuclear, and with gas coming in the last couple for decades. Coal amounts for over 40% of the world's electricity generation. (Oil has been marginal and located where there are abundant oil resources, like the Middle East). In a decarbonising world, the only plausible way of continuing with fossil fuel generation is with Carbon Capture and Storage (CCS). The technologies are known in principle: it requires the separation out of the gas, piping it to a hole on the ground (such as a depleted oil or gas well), injecting it, and then capping it for a long time. Some, like Myles Allen and Stuart Hazeldine (in this issue), think that it will be essential to decarbonisation as the envelop of emissions will be exceeded, and require extractions to take place[20]. In theory, CCS need not be linked to power stations – it could be directly from the atmosphere – but concentrated emissions are probably the most promising route. In terms of practicalities, there are several projects globally, and the use of gas injection to enhance oil recovery is widespread. The key questions about CCS are the cost, and whether it could be conducted on a large enough scale to make a difference. This would require a lot of sinks, and account to be taken of the volume of gas compared to the concentration of carbon in the oil, gas and coal burnt[21].

Beyond CCS, the main electricity options are nuclear and solar – assuming that geothermal is limited for electricity generation (and because of its location)[22], and assuming most of the world's great rivers have been dammed, and that more dams have serious environmental consequences. Nuclear has in theory a lot going for it. It can generate large amounts of electricity in big power stations. There is lots of experience. Japan and France have relied it as their primary source of electricity for decades, and most developed countries have used nuclear. China and India will add more to the energy mix. Nuclear has cost problems, but compared with many of the current renewable technologies, its scale gives it some advantages.

The additional problems with nuclear lie with its full cycle costs, with waste disposal and with social and political acceptability. There has always been the promise held out that technological development would finally deliver nuclear power, which is too cheap to measure and which can consume its own waste, and that safety will be ensured. Yet after half a century the basic designs have not changed much, and with a serious nuclear accident roughly every decade, most of Europe, Japan and the US have fallen out of love with this technology, with a few isolated exceptions. Even if India and China build their planned new nuclear capacity, global nuclear will probably only keep up with the retirements of existing power stations. Given the time spans in building nuclear, it is therefore unlikely to undermine fossil fuels in the first half of this century.

That leaves solar, and here the possibilities are very considerable. If any electricity generation technology is going to undermine the fossil fuels, solar is probably the prime candidate. The reasons are multiple. First, it is abundant and free at source. It is the ultimate form of renewable natural capital[23]: the sun will go on providing it forever, regardless of how much we use. Second, most of the light spectrum is yet to be tapped into. As this expands, the efficiency of solar energy may be increased by orders of magnitude. Third, the current solar panels have great scope for improvement, and new materials like graphene and nano-

[22] Its heat potential is however potentially very large.
[23] On natural capital, see Helm, D. R., 2015b.

technologies make the possibility of game-changing applications possible. Solar film might one day be applied to many surfaces – from buildings to cars and clothes. Solar technology is pregnant with the possibility of scientific breakthroughs in the ways that other ways of generating electricity may not be – short perhaps of nuclear fission. Fourth, solar is decentralised, and if storage can be cracked, its inherent disadvantages of being confined to the day, and better when the sun shines, might be reduced. Finally, the development of large-scale transmission networks, and breakthroughs in cable technologies, might make the sunny areas of the world exporters to the northern and southern regions of the planets.

Storage, and in particular batteries, is the next potential game-changer for the electricity industry. Imagine if attached to every solar device, every wind turbine, and in every house, there was a battery which could store surplus energy and release it on demand. Part of this world already exists: without batteries, much of the economy would grind to a halt. We rely on batteries for our mobile phones, for a host of devices, lights and so on. But a breakthrough in the conventional Lithium-Ion technology or towards alternatives would take the economic structures of the economy into a new framework.

Electric cars may (indeed probably will) become pervasive, and they would in turn play an important role in storage for entire electricity systems. Since transport is one of the main demands for oil (the other is petrochemicals), electric cars would be a major step towards the fossil fuel exit. If electricity is generated increasingly by gas in the transition into a future which might be largely solar, gas would indirectly substitute for oil in this transitory period via gas power stations.

Batteries are only one form of storage. There are lots of others. Heat storage is already common for particular applications, but there is great potential here on a large and small scale. Pumped storage enables the peaks to be managed.

Solar generation, new storage, and electric cars would do considerable damage to the prospects of the oil industry and oil producers. The final part of the electricity vertical chain is at the consumption end, for households, offices and manufacturing. Smart technologies and broadband hubs are increasingly driving household consumption. The Internet-of-Things, the ability to link smart white goods and appliances, heating systems and the charging of batteries and cars will turn this aspect of electricity demand from passive to active, and create great scope to improve energy efficiency. Telsa has already started experimental marketing of household batteries to further facilitate household load management.[24] Buildings more generally will also become smarter – a source of electricity generation through solar panels and solar film, as well as managed demand. The aggregation of data from smart meters – and big data more generally - will facilitate the management of the electricity system as a whole.

Behind the manufacturing demand lays the manufacturing technologies. Three big changes will have their impact through to electricity and energy demand. The first is the new materials like graphene. In the twentieth century, the development of plastics transformed industries and changed the demand for oil and gas. Graphene has remarkable properties – it is a single skin of carbon atoms, with great conductivities, strength, thinness and flexibility. It has been compared in importance to the discovery of plastics. [25]Second, there are new production techniques, notably 3D printing. The ability to digitalise virtually anything means that products can be customised and produced nearer to the points of consumption. It will also change the location, type and amount of energy demands, analogous to the way steel, aluminium, fertilisers, petrochemicals and cement transformed energy demand in the twentieth century. Third, automation - and especially robotics – will change both the location and form of energy demand. 3D printing and robotics point to a disaggregation of production, and a move away from the globalisation of manufacturing more generally, since the advantages of cheap labour in

[24] See for details https://www.teslamotors.com/en_GB/powerwall
[25] For background and references see http://www.nature.com/news/graphene-the-quest-for-supercarbon-1.14193

developing countries is much reduced as robots and automated manufacturing gradually reduce its role.

These predictable technology surprises have two features in common: almost all are general enabling technologies, or combinations of them, of which information technology is at the core; and they will facilitate much more zero marginal cost electricity generation and supply. The former indicates that these changes are likely to be pervasive, and not niches. It is the *combination* of solar, nuclear, batteries and active demand that *jointly* changes the shape of the energy sector and points to a revolution compared with the twentieth century. Together their impact will compound the challenges to fossils fuels.

The latter – zero marginal costs – brings the economics of the Internet to energy. The fossil fuels have all been developed on the back of an energy price and supporting wholesale markets, to which long-term take-or-pay contracts have been linked, and often indexed. An energy world, which looks more like the communications industry, would be very different. Indeed it already is: the wholesale electricity markets have witnessed falling energy prices as renewables penetration has been going up. This, in turn, creates a very real difficulty for fossil fuels electricity generators, who are effectively expropriated. The zero marginal cost technologies are paid for though fixed price contracts. The economic guts of the electricity industry therefore start to shift to fixed price capacity contracts, and away for the traditional pool-type models. To date, the fossil fuel generators have not been able to find a solution to this zero-marginal cost world.

5. Policies for a technological revolution

Energy technology policy, and energy policy generally, is traditionally very pedestrian. There has been little technical change in the twentieth century, and until recently it has been reasonable to assume the future will look like the past. This is no longer a safe assumption. Whereas the coal-fired power station (nineteenth century), the internal combustion engine (nineteenth century), the gas turbine (1940s) and the PWR (1950s) have dominated, all are challenged by the new technological revolutions described in the previous section.

What then should policy makers do? The first challenge is to the producer countries of fossil fuels and their depletion policies. Whereas it has been a safe assumption that leaving oil and gas in the ground would benefit from rising prices, this is no longer obviously the most efficient policy. If the commodity super cycle is over, if peak oil does not stand up to inspection, if new zero marginal cost technologies are coming along, if electricity is growing in market share, and if transport is going electric, then the medium to long run might witness *falling oil and gas prices*. Now the oil and gas is worth more today than tomorrow, and hence it makes sense to maximise production now. The consequence may be self-fulfilling: higher production will lower prices.

The second policy challenge relates to R&D. The solution to climate change is unlikely to lie with top down political frameworks and agreements like Paris. Existing solar and wind generation technologies are incapable of making much impact**,** and *existing* large-scale nuclear will take time, if it ever is part of the solution. [26] New technologies are therefore essential to decarbonisation. Yet the main characteristics of existing carbon policies are that they devote large-scale subsidies to existing technologies and trivial amounts to R&D. This imbalance is at best inefficient.

The third policy challenge is the shorter-term need to address the rising emissions, *before* the new technologies kick in. The obvious path to follow is to get out of coal quickly. Since current renewables cannot fill the void, a coal-to-gas switch is in many cases the only practical alternative. Given the abundance of gas, its price and the fact that new gas power stations can be built quickly at a relatively low cost, a focus on a combination of a carbon price and emissions performance standards to drive out coal is likely to be the efficient policy framework.

[26] See MacKay (2008).

The fourth policy challenge is to energy systems, system development and the energy infrastructure. Part of this lies with smart data, but it is also about interconnection and the development of new infrastructures to support electric cars and decentralised and stored electricity. Interconnections and network development as a public good to the systems as a whole are efficient policies in the face of the inevitable uncertainties. They also maximise competition and security, and hence are one of the few measures that help all three policy objectives – security of supply and competitiveness, as well as de-carbonisation.

6. Conclusions

The end of fossil fuels is not about to happen anytime soon, and will not be caused by running out of any of them. There is more than enough to fry the planet several times over, and technological progress in the extraction of fossil fuels has recently been at least as fast as for renewables. We live in an age of fossil fuel abundance.

We also live in a world where fossil fuel prices have fallen, and where the common assumption that prices will bounce back, and that the cycle of fossil fuel prices will not only reassert itself but also continue on a rising trend, may be seriously misguided. It is plausible to at least argue that the oil price may never regain its peaks in 1979 and 2008 again.

A world with stable or falling fossil fuel prices turns the policy assumptions of the last decade or so on their heads. Instead of assuming that rising prices would ease the transition to low carbon alternatives, many of the existing technologies will probably need permanent subsidies. Once the full system costs are incorporated, current generation wind (especially offshore) and current generation solar may be out of the market except in special locations for the foreseeable future. In any event, neither can do much to address the sheer scale of global emissions.

New policies are urgently needed for this very different world. The primary focus on the climate change side – and the only serious reason for optimism – many lie with the new and emerging technologies. The energy sector is moving from a century with very little fundamental technical change to one where almost every dimension is being profoundly disrupted. Next generation solar is likely to play a key part but so too are driverless and electric cars, new batteries for the home and for the intermittent generators, smart grids, smart meters and a host of changes in the demand side, induced by the changes being brought about through new materials like graphene, new processes like 3D printing, and new automation methods like robotics.

It is these fundamental technological changes that will alter the cost structures of the energy and particularly the electricity industries. They will change the composition of supply and demand, and they will bring the economics of the internet – in particular zero marginal costs – to the energy sector. The overriding priority of energy and climate policies should be to assist this technological transformation, rather than devoting large subsidies to existing renewables. These have the best chance of ending the age of fossil fuels.

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