The University Of Sheffield.

SPERI Paper No.6

The UK's Innovation Deficit & How to Repair it.

Richard Jones

speri. Sheffield Political Economy Research Institute.

Pr

About the author

Richard Jones

Richard is Pro-Vice-Chancellor of Research and Innovation at the University of Sheffield. He is an experimental polymer physicist who specialises in elucidating the nanoscale structure and properties of polymers and biological macromolecules at interfaces. In 2006 he was elected a Fellow of the Royal Society, and in 2009 was awarded the Institute of Physics Tabor Prize for his contributions to nanoscience. He was the Senior Strategic Advisor for Nanotechnology for the Engineering and Physical Sciences Research Council (EPSRC) from 2007 to 2009. In 2013 he was appointed to the Council of the Engineering and Physical Sciences Research Council (EPSRC).

ISSN 2052-000X

Published in October 2013

speri. Sheffield Political Economy Research Institute.

1. Introduction

Technological innovation is one of the major sources of long-term economic growth in developed economies. Since 1945 countries like the UK have enjoyed a remarkable run of sustained growth and improvement of living standards, associated with the widespread uptake of new technologies – cars and aircraft, consumer goods, computers and communication devices, effective new medicines, all underpinned by the development of new materials, chemicals and electronics. Now the UK is undergoing its deepest and most persistent period of slow or no growth for more than a hundred years. Is there any connection between this growth crisis and innovation – or lack of it?

The UK is a much less research and development intensive economy than it was thirty years ago, and is less research and development (R&D) intensive than most of its rivals; this R&D deficit is most prominent in applied research funded and carried out in the business sector and in government funded strategic research. Innovation can and does happen without research and development as understood in its conventional sense; innovation through organisational change and novelty in marketing, often using existing technology in new ways, can make significant contributions to economic growth. But at the technological frontier the development of new products and processes requires targeted investment of people and resources, and it is the capacity to make such efforts that is lost as research and development capabilities are run down. This loss of innovative capacity is not an accident; it is a direct consequence of the changing nature of the UK's political economy. In the private sector, a growing structural trend to short-termism driven by the excessive financialisation of the economy, and an emphasis on 'unlocking shareholder value', has led to an abandonment of more long-ranged applied research. The privatisation of sectors such as energy has brought these pressures for short-termism into areas previously thought of as of strategic importance for the state. Together, these factors have led to the systematic liquidation of a significant part of the national infrastructure – both public and private - for applied and mission-oriented research.

Research and development are global activities; the benefits of new technologies developed in one part of the world diffuse across national boundaries, so R&D needs to be considered in a global as well as a national context. The declining R&D intensity of the UK displays in the most acute form a wider problem - highly financialised market-centred capitalism, while it is it is good at delivering some types of incremental, consumer focused innovation, does not favour more radical innovation which requires larger investments over longer time horizons. We currently are seeing serious global slowdowns in innovation in the pharmaceutical sector and in energy sectors. The former is a particular problem for the UK, because has a strong specialization in the pharmaceutical sector. The slowdown in energy innovation is a problem for everybody on the planet.

The example of energy illustrates why the development of new technology is so important. We depend existentially on technology, to deliver the cheap and abundant energy that our economies depend on, for example. But the technology we have is not good enough; the cost of extracting fossil fuels from the earth rises as the most accessible reserves are exhausted, and the consequences for the stability of the earth's climate of burning fossil fuels become ever more apparent. We need better technologies not just to ensure the continuously rising living standards we have come to expect, but also because if we do not replace our currently unsustainable technologies with better ones living standards will fall.

We should not be fatalistic about a slowing down of innovation in crucial technology areas, either nationally or globally. The slowing down of innovation is not a consequence of some unalterable law of nature, nor is it because we have already 'taken the low-hanging fruit'. Innovation is slowing down because we have collectively chosen to devote fewer resources to developing it. We need as a society to recognize the problem, recognize that current policy for innovation is not delivering, and take responsibility for changing the current situation.

2. The UK's current growth crisis follows a sustained period of national disinvestment in R&D

There is a well-established narrative about the performance of the UK economy since the 2nd World War. This is often framed in terms of a long-term decline up to 1979, whose causes have variously been ascribed to inflationary fiscal and macroeconomic policies, poor industrial relations and widespread restrictive practises, poor management, and a variety of cultural factors (see e.g. Tomlinson, 1996). The market oriented supply-side reforms, involving financial deregulation and privatisation introduced by the 1979 Conservative government, and essentially continued by subsequent governments of both parties until the present day, are widely held to have reversed this trend of decline (see e.g. Card and Freeman, 2002), at least until the onset of the 2007 financial crisis.

The story of the UK economy is generally told in comparative terms – whether the UK is doing better or worse than Germany and France. From the point of view of peoples' living standards, though, what matters is absolute, not relative, performance. If we express the absolute performance of the UK's economy in terms of the single number that is most closely related to the wealth of the nation as it feeds into individual household incomes – the real GDP per person – we see a different story. The graph of figure 1 shows that the post-war period saw remarkably steady growth in GDP per person. Between 1948-79 this measure grew at a steady annual rate of just under 2.6% a year compounded. Even the tumultuous years of the 1970s result in rather small deviations from this trend, in the shape of a brief boom in 1972-3 followed by a short and sharp recession.

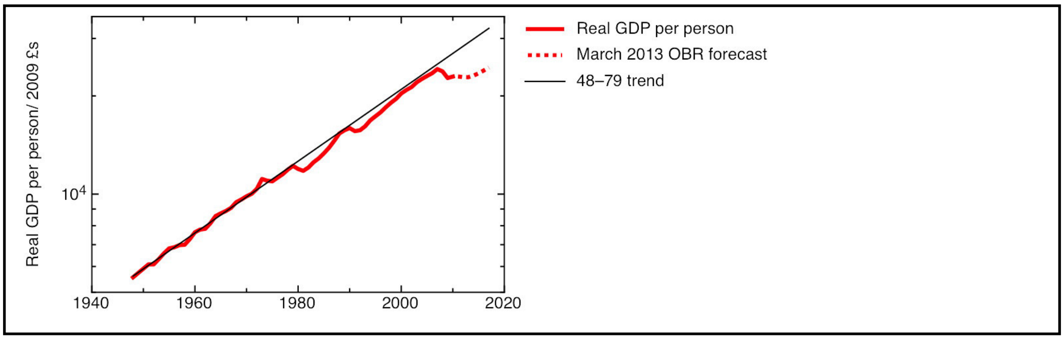

Figure 1: Real per capita GDP since 1948. Data sources: solid line, 2012 National Accounts; dotted line, March 2013 OBR forecasts corrected for rising population using ONS population projections

The pattern distinctly changes in 1979, with a long and deep recession followed by a period of faster growth. The late 1980s saw growth at rates faster than the 1948-79 trend, but this growth proved to be unsustainable and was followed by another recession. Similarly the recovery from the early 1990s recession, which was sustained right until the 2007 financial crisis, was also initially at growth rates faster than the 1948-79 trend. However, in neither case was the faster post-recession growth rate sufficient to make good the losses sustained in the preceding recessions - the absolute value of per capita GDP did not recover to the pre-1979 trend line.

It is striking that, despite the many evident weaknesses of the 1948-79 UK economy, on this measure its overall performance was still superior to more recent experience. If the supply-side and labour market reforms introduced after 1979 improved the UK economy's growth potential, then there must have been some even more potent countervailing negative contributions.

To bring the story up to date, the graph makes clear how exceptional in post-war experience the recession following the 2007 financial crisis has been. Even with the beginnings of a recovery in GDP growth, there is a huge gap to be made up. This is made very clear in the plot of figure 2, where GDP per person is plotted in terms of its deviation from the 1948-79 trend line. In order to begin make up the lost ground, GDP would need to grow at a rate faster than about 3.2% (accounting for current population growth of around 0.6%), for a sustained period of many years.[1]

It is widely known that there was a discontinuity in UK economic policy in 1979. What is perhaps less well appreciated is the long-term decline in the research and development intensity of the UK's economy that has taken place since 1979, and in particular in the period up to 2000. This is also illustrated in figure 2, which shows total UK expenditure on R&D – including government and private sector spending – as a fraction of GDP.

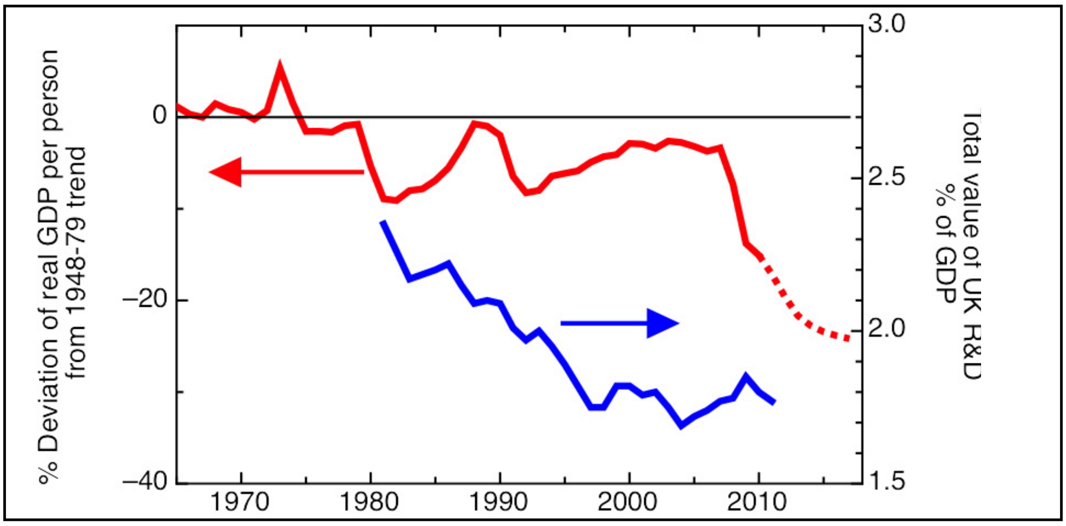

Figure 2: The British growth crisis. Red, left axis. The percentage deviation of real GDP per person from the 1948-1979 trend line, corresponding to 2.57% annual growth. Sources: solid line, 2012 National Accounts. Dotted line, March 2013 estimates from the Office for Budgetary Responsibility. Blue, right axis. Total R&D intensity, all sectors, as percentage of GDP. Source: Eurostat

In 1979 the UK was one of the most research-intensive economies in the world. Now, amongst advanced industrial economies, it is one of the least. As figure 3 shows, while in the UK's R&D intensity was declining, not only have the UK's traditional competitors – the USA, Japan, France and Germany – maintained or increased their R&D intensity, but there have been dramatic increases in R&D spending from rapidly developing countries such as South Korea and China.

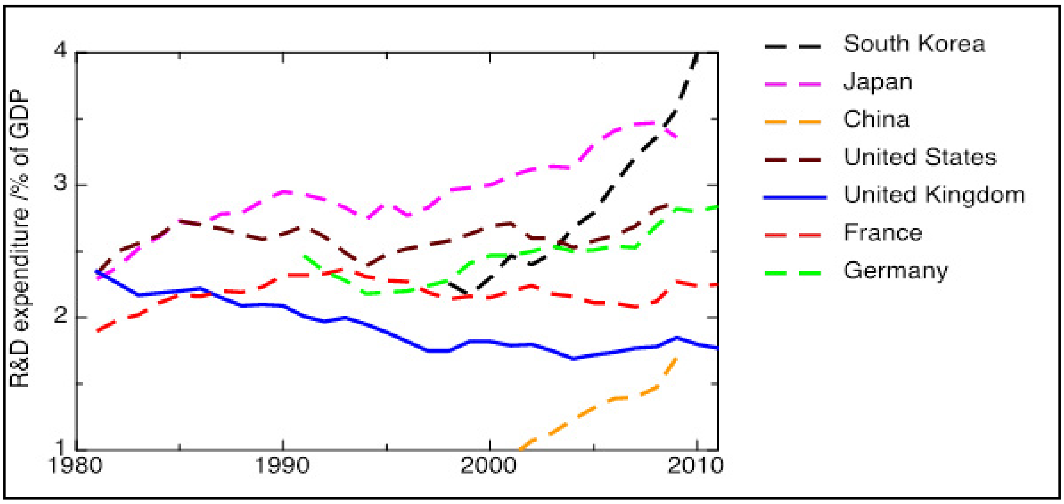

Figure 3: R&D intensity of selected economies over the period 1980-2011, expressed as Gross Expenditure on R&D as a fraction of GDP. Source: Eurostat.

Our current growth crisis, then, follows thirty years in which the UK has disinvested in research and development. The nature of the link between the R&D intensity of an economy and its economic performance is not straightforward, but if one is looking for contributing factors to the poor performance in the UK this may be one place to start. The aim of this paper is to explore the roots in political economy of the UK's innovation deficit; to do this we first need to identify the sectors in which this decline in R&D has been most marked.

3. The overall decline in the UK's R&D intensity has been driven by a long-term decline in private sector R&D

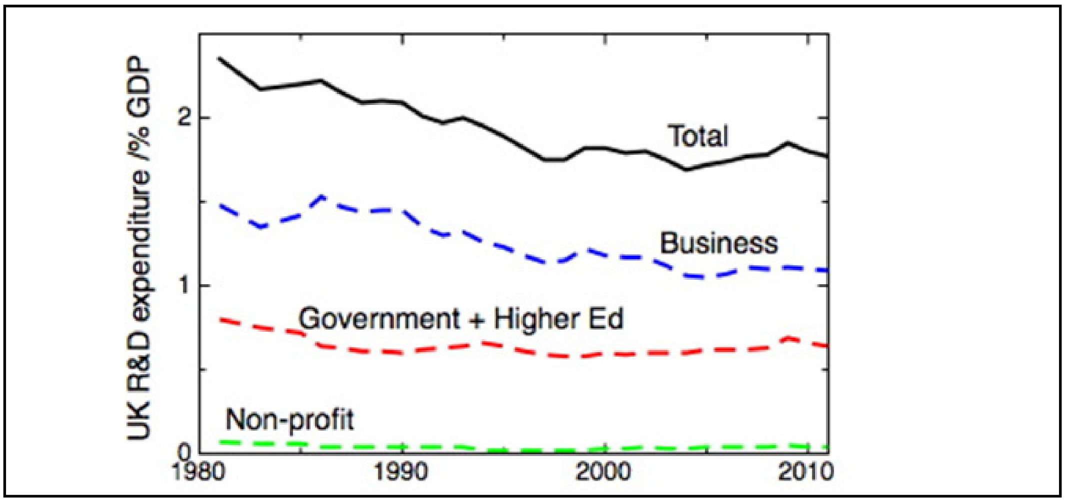

Figure 4: Value of UK R&D performed by sector as %of GDP. Source: Eurostat

The UK is not just unusual among developed economies in its declining R&D intensity; it is also an outlier in who funds research and where it is carried out. Figure 4 breaks down the UK's R&D by the sector in which it is carried out. The decline in business R&D is marked.

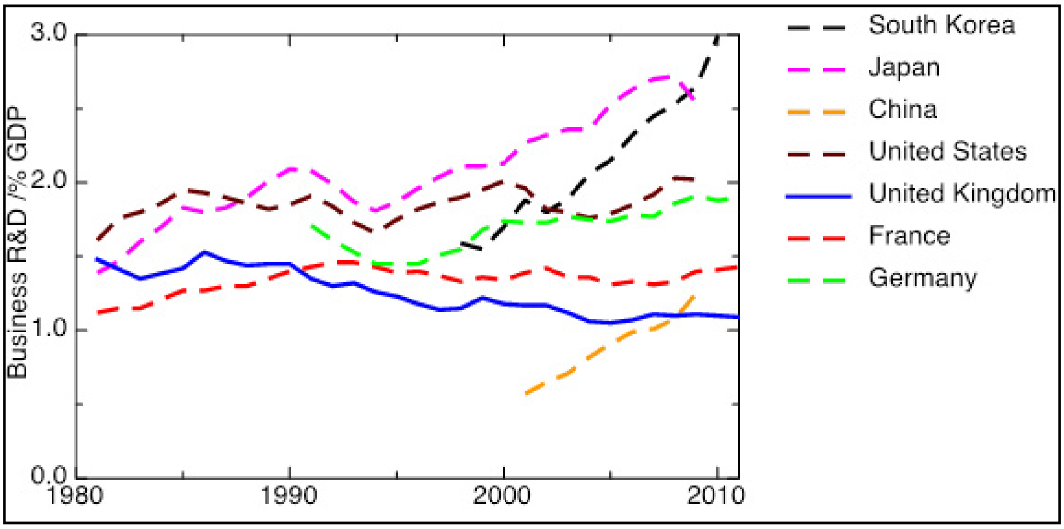

Figure 5: Value of R&D performed in the business sector, as a fraction of GDP. Source: Eurostat

As figure 5 shows, this decline in business R&D intensity is unique amongst major competitor nations. If we look, not at where R&D is carried out, but at who funds it, the anomalous situation of the UK becomes even more marked. In most leading economies, the majority of R&D is funded by business enterprises (Hughes and Mina, 2012); only in the UK and Norway is this fraction less than one half. Not only is the fraction of GDP spent on business R&D less in the UK than all its major competitors, this fraction fell between 1999 and 2009 (see exhibit 23 in Hughes and Mina, 2012).

At the same time as competitors were becoming more research intensive, UK industry was becoming less research intensive. Germany, Denmark, the USA, Korea, Japan, Sweden and Finland all have industrial sectors devoting substantially more than the UK to R&D, in the last four cases more than twice as much. Notably, during this decade business enterprise R&D as a share of GDP in China more than doubled, surpassing that of the UK.

It is sometimes argued that the low and decreasing R&D intensity of the UK economy simply reflects changes in the structure of the economy. But even if we focus on the business enterprise R&D in the manufacturing sector, we find a relatively small share of total value added spent on R&D (Hughes and Mina, 2012). It is not just that the manufacturing sector has become smaller, it is that the UK's manufacturing sector has a lower R&D intensity than other developed countries.

Before the current financial crisis and subsequent recession, some regarded the fact that GDP growth rates were high despite the UK economy's low R&D as a paradox that demanded explanation. This led to a search for types of innovation not captured in conventional measures of research and development (NESTA, 2009). This line of argument leads to many valuable insights, for example on the importance of innovation in the service sector, and stresses the importance of having a suitably wide definition of innovation. However, as I argue below, not all innovation is the same. While many innovations can take place without formal research and development programmes, particularly when they take place in the digital realm, innovations in the material and biological realms do require the sustained investment of money and manpower that an R&D programme provides. Moreover, given the poor performance of the UK economy since the financial crisis, the original paradox does not seem so pressing any more.

4. The death of the UK's corporate laboratories

Why has private sector R&D fallen? There has been much focus on the role of fast growing small and medium sized enterprises in driving innovation, but the reality is that private sector R&D is predominantly driven by the large firms with the resources and organisational structure to sustain such efforts. According to Hughes and Mina (2012), in 2009 only 3.5% of R&D in the UK was done by the independent SME sector. The largest 10 R&D spenders, on the other hand, between them accounted for 34% of the UK's R&D.

R&D expenditure by companies is a long-term investment. The decline of company R&D should therefore be considered as part of the bigger picture of changing investment patterns, and in particular as one consequence of an identified tendency to irrational short-termism in UK companies (Kay, 2012). Haldane (2011) gives quantitative evidence on short-termism from an analysis of equity pricing; this demonstrates an overall increase in short-termism from the period 1985-1994 to 1995-2004. The worst offender is the materials sector, which with the health sector showed short-termism in both periods, but by the second of these periods short-termism existed over all sectors - 'evidence of a rising tide of myopia', in Haldane's words. Short-term thinking implies that long-term projects that would produce positive returns with realistic discount rates are rejected; this means that too little long-term investment is made, and what investment is made goes into projects with a short-term return that a rational assessment would suggest would deliver lower total returns. This is a market failure that leads to the misallocation of resources and, ultimately, the expectation of lower overall growth rates.

What has squeezed out long-term investment? For large, quoted companies, it is not due to a lack of cash (unlike the case for small start-ups) – the majority of R&D spending is generated from retained earnings (60-65%, according to figure 41 in DBIS, 2011). Instead, one should look to the structure of the equity markets, and the bias this imposes towards short-term returns. At all stages in the investment chain there is a 'bias towards action' which leads to too high a level of merger and acquisition activity; managers, traders, analysts, investment bankers all benefit from trading activity rather than building businesses. Owners and beneficiaries benefit from long-term absolute performance, but asset managers are judged on short-term relative performance. Successful, long-term research and development activities that ultimately lead to new product areas contribute to long-term growth but cost money in the short term.

This is part of a wider correlation between the excessive financialisation of the economy and low productivity growth (Cecchetti and Kharroubi, 2012). Credit booms, like other bubbles, take resources away from more productive uses, in particular from the R&D intensive sectors that are the long-term engines for growth. These include human resources – successful R&D depends on a relatively small cadre of highly talented and skilled workers, many of whom have in recent years been attracted to work in the financial sector. Perhaps the fabled 'rocket scientists' in the City would have been doing more good if they had actually been working for the aerospace sector.

The problems of excessive financialisation and endemic short-termism have long been identified as a peculiar feature of the variety of capitalism practiced in the UK (Watson and Hay, 1998). This perhaps accounts for the fact that worldwide trends in this direction have had a particularly marked effect in the UK.

The process by which innovation capacity in large corporates was lost is illustrated by the example of two companies, ICI and GEC. Up to the 1990s, the corporate laboratories of these two companies were major vehicles for innovation and technology translation in a variety of areas across electrical engineering, electronics, chemicals and pharmaceuticals.

Pressure on ICI began in 1991 with a hostile takeover bid from a conglomerate with a reputation as a corporate raider, Hanson. This bid was unsuccessful, but it fuelled a perception that a corporate reorganization could realize quick returns for shareholders, and ICI itself demerged in 1993. The demerger created a new company – Zeneca – which combined ICI's pharmaceutical business with agrochemicals and some speciality chemicals businesses. Zeneca evolved further – its agrochemical business was spun off into a Swiss-based company, Syngenta, the speciality chemicals businesses were disposed of into a privately held vehicle called Avecia, and the pharmaceutical business was merged with the Swedish company Astra to form AstraZeneca.

Meanwhile, the rump of ICI, comprising businesses making bulk chemicals, polymers and paints, underwent its own transformation. The strategy was to exit the cyclical bulk chemical and polymer businesses, and to move into higher added value speciality chemical businesses. The strategy was executed by the purchase in 1997 of the speciality chemicals divison of Unilever, but the deal, financed with borrowed money, was mispriced and badly timed. The company struggled under the burden of debt it had incurred, making major divestments to the US chemical company Huntsman and the privately held, Swiss-registered company Ineos, before finally succumbing to a take-over of the rump of the company by the Dutch firm Akzo-Nobel in 2008.

ICI was the victim of the notion that the best way to renew an established technology-based business is by corporate reorganization, through mergers and acquisitions, rather than by developing new, high-value products through research and innovation. The story of GEC has some echoes of this, with the added complication that its crucial acts were played out against the background of an unsustainable bubble in the valuations of ICT companies.

In 1996 Lord Weinstock stepped down from running GEC, which he had built up into the UK's leading manufacturing company, operating in a variety of electrical and electronics-based businesses. Under new leadership, the company adopted a new strategy, making a number of re-organizations, culminating in the sale of its defence businesses to British Aerospace in 1999. Seeking to reorient itself as high-tech company, it used the cash to buy businesses in the then-booming telecoms sector, at prices that subsequently turned out to be much too high. The company, now renamed Marconi, was forced to restructure in 2003 after the bursting of the *dot.com* bubble, and finally collapsed in 2005, with the remaining assets sold to the Swedish telecoms company Ericsson.

In these two examples, two decades of frenetic deal making may have benefitted investment bankers and corporate lawyers, but the outcome has been that neither company exists in its original form. AstraZeneca continues the pharmaceutical activities of ICI, but in the chemicals and electronics sectors the net result has been a major reduction in the capacity of the UK to innovate. Some activities continue in the successor companies, but the scale of R&D activities carried out in these operations is very much smaller. This situation is to be contrasted with that in Germany, where the erstwhile rivals of GEC and ICI, Siemens and BASF, continue to operate highly innovative businesses successfully and at scale.

The corporate laboratories exemplified by ICI and GEC were certainly not without their negative features. While they sheltered science from the capital markets, there was always a danger that the application of the science discovered was constrained to existing business units of the parent company. Occasionally innovations that were felt to be valuable but which did not fit the interests of existing businesses were commercialised through spin-outs, but many innovations from corporate laboratories were left unexploited. On the other hand, it has often been argued that corporate laboratories can be barriers to bringing in technology developed elsewhere. But, from the point of view of those investors arguing for a more rapid release of shareholder value, the key objection was more fundamental; to them the idea of a technology based conglomerate investing substantially in long-term R&D distorted the workings of the market in allocating capital.

At the heart of the business model of technology-based conglomerates like ICI and GEC was the idea that one would use the income streams from established businesses to fund the research that would lead to future products and new businesses. The view of market fundamentalists was that this income, rather than funding R&D at the discretion of the business's managers, should be returned to shareholders, who would make their own decisions about what potential new technologies to invest in in the open market. In this view, companies based on old technologies would inevitably fade away, but fast-growing new companies exploiting new technologies would replace them.

This has not happened in the UK. Old technology-intensive companies certainly faded away, but, as we shall see, they were not replaced by enough new ones of the same scale. It seems that the market took a shorter-term view than the managers of the technology businesses. When the market did take an interest in new technology, it ended up fuelling speculative bubbles like the *dot.com* boom, in which capital was misallocated on a massive scale to fund innovation that in many cases did not ever deliver useful results and profits. In short, the market proved to be less rational in allocating resources than the managers of the technology combines had been.

5. The international landscape for business R&D

2011 marked another milestone for research and development in the UK – in this year, for the first time, more money was spent on R&D in the UK by foreign owned businesses than by UK owned businesses. As figure 3 shows, from 2000 R&D expenditure by UK businesses has slightly fallen in real terms; the small real terms increase in total business R&D spend was driven entirely by a significant rise in R&D inward investment.

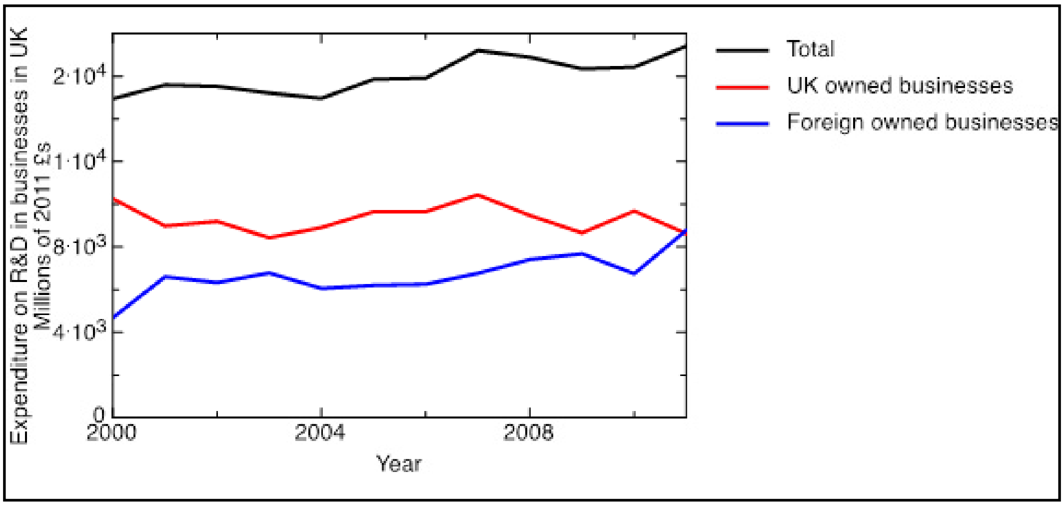

Figure 6: Value of R&D performed in the UK by the business sector by ownership. Source: ONS, 2011

This increase in overseas funded business R&D is not unique to the UK, and it can be thought of as part of the general trend to a more globalised economy. However, in absolute terms the UK is the largest recipient of inward R&D investment by a considerable margin. It is certainly positive that the UK is perceived from abroad as a good environment for science; the inward investment is associated with high level employment for UK citizens, is likely to lead to improve the level of innovations and skills in other companies, and may be associated with larger-scale inward investment to support other activities like manufacturing. On the other hand, the UK based R&D facilities of foreign-owned firms may be more at risk of closure in challenging economic times, as has recently happened in the pharmaceutical industry. And the UK may be in less of a position to benefit from foreign-owned companies that do grow fast than it would be if those companies were UK-owned.

Given that the UK has a lower business R&D intensity than competitors (as shown in figure 2), and that it has an unusually low fraction of R&D funded by UK-owned companies, it follows that the R&D performance of UK owned companies must in aggregate be significantly weaker than those of competitor nations. We can examine this question at the firm level by reference to the 2012 EU R&D Scoreboard (European Commission Joint Research Centre, 2012). This tabulates the R&D spend of 1500 companies worldwide that in 2011 each invested more than €35 million; between them they account for the majority of private-sector-funded research in the world. The top 100 companies account for 57.2% of the R&D tabulated in the scoreboard. Among the top 100 companies are 34 from the USA, 25 from Japan and 11 from Germany. Only 3 UK companies appear in the top 100 – the two pharmaceutical companies, GSK and AstraZeneca, and the part-nationalised bank RBS (the definition of R&D used in this table includes spending on the development of in-house IT systems).

Other R&D intensive companies do exist; further down the list one finds companies like Rolls-Royce (161), Vodafone (249), ARM (413) and CSR (414). The problem is not that these, and other companies, are not excellent, innovative companies; it is that they are not big enough and there are not enough of them.

The domination of UK-owned, R&D-intensive businesses by the pharmaceutical sector has positive and negative aspects. Historically, this is a sector that has delivered high margins and high growth, and it is linked to a fundamental science base in life sciences that is very strong. However, there are risks in being so exposed to a single sector, particularly when that sector - the pharmaceutical industry - has some deep-seated problems of its own. These difficulties are discussed in the next section.

6. The trouble with pharma

The dramatic pace of technological change in the information technology industry is summed up by Moore's law;[2] the cost of computing power has been falling exponentially. This prompts some to assume that this kind of accelerating innovation is common to all technology sectors. The pharmaceutical industry, however, represents a counter-example. Despite a period of extraordinarily rapid advance in the basic sciences of molecular and genomic biology, the productivity of R&D in the pharmaceutical industry is not increasing, but decreasing. By 2010 it took an average of $2.17 billion in R&D spending to introduce a single new drug, including the cost of all the failures. This cost per new drug has been following a kind of reverse Moore's law, increasing exponentially in real terms at a rate of 7.6% a year since 1950, corresponding to a doubling time of a bit more than 9 years (Scannell et al.,2012).

This R&D effort is sustained by the healthy revenues pharmaceutical companies achieve from existing medicines when they are under patent protection. But, as the supply of new drugs falters and patent protection on existing ones expires, it becomes more difficult for pharmaceutical companies to justify large R&D expenditures to their investors. Indeed, in the opinion of some market analysts, the market currently assigns no value at all to their R&D enterprise.

One response has been to reorganize, trying to rationalize the industry through mergers and acquisitions, or to change the way research and development is done. The effect is to reduce total expenditure on R&D (Mattina 2011); one of the world's largest pharmaceutical companies, Pfizer, is currently executing a plan to reduce R&D expenditure. This fell from $9.4 billion in 2010 to $7.8 billion in 2012, with further cuts to come. This has involved the closure of famous laboratories like its site in Sandwich, UK. If the markets are right about the net present value of pharmaceutical R&D, decisions like this are entirely rational financially, but they will not help the development of new medicines for our many pressing unmet clinical needs.

What seems at first to be a more positive response is the idea that fast-moving new biotechnology companies can exploit the new science emerging from universities and develop innovative new therapeutic approaches which, if they show signs of working, can be acquired by big pharmaceutical companies at a later stage. It is certainly the case that more and more new therapeutic molecules are biological species, rather than the small molecules of traditional medicinal chemistry - antibodies and antibody fragments, other proteins and peptides, and perhaps soon nucleic acids like the si-RNAs. Some of these molecules have already had a significant clinical impact (e.g. herceptin and avastin), but the idea that there has already been a biotechnology revolution is probably overstated (Hopkins et al., 2007). The story of monoclonal antibodies suggests that it can take as much as 25 years for fundamentally new developments in biomedical science to make a significant impact.

One problem is that the venture capital money small biotech start-ups rely on is hard to get, and this seriously limits the scale of the sector. The total invested by VCs in biotech and pharma in the UK in 2012 was just £38 million (British Venture Capital Association, 2013) - a tiny fraction of the annual total R&D spend of the pharmaceutical sector in the UK, which was £4.85 billion in 2011 (Office of National Statistics, 2011). The financial crisis has hit venture capital hard - there has been more than a four-fold drop in investment in biotech and pharma since 2006. Another issue is that the cost base of UK biotech start-ups –particularly their management costs - may be high in relation to the relatively low capitalization of the sector. In 2008, it was reported that boardroom remuneration alone drained £40 million a year from the sector (Smith et al., 2009).

The final response is to rely even more on the state and the non-profit sector for this R&D funding. We need to remember how much state funding already goes in to provide the underpinning advances in life sciences that the pharmaceutical and biotechnology industries depend on. This is dominated in the USA by the huge budget of the National Institutes of Health - $38 billion. But, even in the UK, the Medical Research Council spends £550 million, the Wellcome Trust spends another £750 million, and big medical charities put in substantial further sums - £330 million from Cancer Research UK, for example, this largely arising from individual donations and fundraising. The difficulties of the pharma and biotech industries put pressure for more of this state and non-profit spending to be moved downstream, closer to the clinic and the market. The result is an increasing number of calls for translational funding, and schemes such as the £180 million in the Biomedical Catalyst Fund, providing government grants directly to start-up companies. In fact, substantial amounts - perhaps the majority - of the funding directed to start-up companies through venture capital funding originates from government agencies of one sort or another (the total money raised by venture capital and private equity from government agencies in 2012 - £424 million - actually exceeds the total investment in technology companies, but of course some of the government investment will have been into non-technology areas).

There is no question that the last twenty or thirty years has brought astonishing progress in our fundamental understanding of the life sciences. But, for all our scientific success in creating fundamental understanding of biology, our current system of innovation is not as successful as it should be at translating that into better health, and the situation seems to be getting worse rather than better. This is a global problem, but it is particularly important for the UK because of the nation's strong specialization in the sector.

7. Privatisation and the end of strategic science

Historically, governments like those of the UK have supported two types of science. 'Basic science', not motivated by direct applications, has been supported on the grounds that it brings economic gains to the nation that cannot be captured by an individual private sector sponsor. In a different category is 'strategic science', science which directly supports the strategic imperatives of the government. Such imperatives could include defence, the infrastructure to support the free operation of markets (i.e. standards and regulation), the protection of the environment, national communications infrastructure and the security of energy supply.

As political philosophies change, strategic science can be affected in two ways. The range of activities that are considered strategically important can evolve. In the early to mid-twentieth century, for example, many countries considered a capacity to make steel to be a strategic imperative. Now, most countries would consider steel to be a commodity, best made in whatever country has comparative advantage. The move to privatise many areas of government activity represents a shrinking in the boundaries of what the state considers to be strategic, and the level of associated research and development in the areas after privatisation will reflect a commercial assessment of rates of return on investment, subject to the same pressures towards the short-term discussed in the context of large corporations. As we will see with some examples, this shift has generally led to a decrease in the level of research and development.

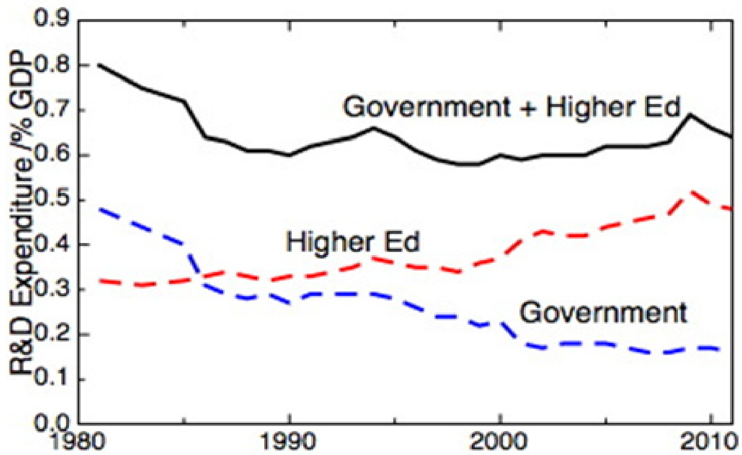

Figure 7: UK R&D performed in the government and higher education sectors. Source: Eurostat

Even in those areas that the state still regards as strategic – notably defence – there remains a question of where the supporting research should be carried out. Even if the area of activity is still regarded as strategic for the state, it might still be possible to procure the research and development to underpin the area by contract from the private sector. In the twentieth century, the UK built up a very substantial infrastructure of state-run research establishments to develop new defence technologies (Edgerton 2005). At the end of the Cold War, there has been a substantial run-down of these establishments, followed by a privatization of a major part of the research effort in the form of the company Qinetiq. This now operates as a contract research organization, with the UK government accounting for just over a third of its revenue.

One very significant area in which the proposition that the market could meet the strategic aims of the state has been put to the test is in energy supply. Our industrial society depends on access to plentiful, convenient, cheap energy, and the rapid economic growth of the last two hundred years has been underpinned by the large-scale use of fossil fuels. The burning of those fuels has resulted in a marked increase in the carbon dioxide content of the atmosphere, resulting in a changing climate with potentially dangerous but uncertain consequences. Given that existing low-carbon energy sources are expensive and difficult to scale up, it should be a strategic imperative to research new or improved, low carbon energy technologies.

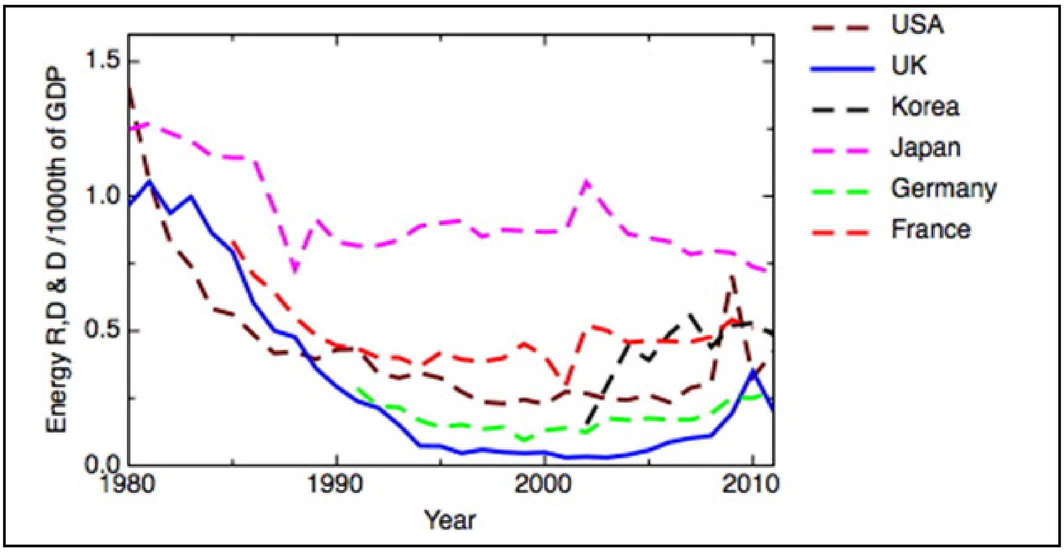

Figure 8: Governemt spending on energy research, development and demonstration as a fraction of GDP. Data: International Energy Agency

On the contrary, the thirty years from 1980 has seen a precipitate drop in government funding for energy research, development and demonstration (RD&D) in the UK (International Energy Authority, 2013). The UK is not unique in this; energy RD&D in the USA has also dropped (Nemet and Kamman, 2007). Only Japan sustained anything like its earlier intensity of energy research into the 1990s, and a rapid post-2000 growth of energy RD&D in Korea is an exception to the general picture. But the UK's position has been the most extreme; as the graph shows, at its lowest point the fraction of GDP dedicated to energy RD&D by the UK government had fallen to an astonishing 0.2% of its 1981 high point.

Part of the story in the UK relates to a major wind-down of the UK's programme in civil nuclear power, which was well under way by 1986, when the Atomic Energy Authority, the UK government agency responsible for research into civil nuclear power, was made into a 'trading fund', in preparation for privatization. AEA Technology Ltd was duly floated in 1996, with a rump of the UK Atomic Energy Authority left to decommission nuclear legacy sites and manage the UK's participation in international fusion research. The privatized AEA Technology attempted to make its way as an energy and environmental consultancy, but the company finally went into liquidation in 2012, with its assets subsequently being acquired by the engineering company Ricardo. In 1981 civil nuclear power accounted for 68% of the energy R&D budget, so the winding down of this programme accounts for a substantial fraction of the loss of energy R&D - but not, as we shall see, all of it.

The definitive story of the UK's civil nuclear programme has yet to be written. That story will include some engineering brilliance, some dismal economics,[3] and an expensive and dangerous legacy of waste and decommissioning, many of whose most undesirable features reflect a deeply entangled relationship with the nuclear weapons programme. The run-down of civil nuclear research will have been welcomed by an unlikely alliance of free-marketeers and green campaigners. But now we are in a situation where even some environmental campaigners are thinking that, if we are to have any hope of limiting climate change, we will need nuclear power. From a national perspective this means that this technology will need to be imported. And, because the slow-down in civil nuclear power research has been global, the only technologies that are currently available are essentially incremental upgrades of 1970s designs.

But even in the 1970s and 1980s, nuclear research was not the only energy research going on. In 1983 non-nuclear research, development and demonstration was £104 million, 34% of the total. By 2001 spending on non-nuclear energy research had declined to £16 million in cash terms (another £15 million was spent on what was left of the nuclear programme, including the UK contribution to the Joint European Torus, an international fusion energy research project based in the UK). This is an astonishingly small number, given that the turn-over of the UK energy industry at the time accounted for about 2% of GDP (excluding oil and gas extraction), and given the central importance of energy to a modern economy.

To explain this remarkable decline, we need another date. In 1990 the UK's electricity industry was privatized, resulting in ten years of corporate reorganizations (Helm, 2004). The interests which acquired this national infrastructure found it more profitable to use financial engineering to extract cash from these assets than to invest in it, particularly if those investments - such as research and development - were long-term in nature. In 1994, in the privatized utility sector as a whole (comprising electricity, gas and water supply), £170 million was spent on R&D. The government, meanwhile, believed that the magic of a competitive market was the best way of ensuring the long-term security of energy supplies. As the mergers and acquisitions played out, by 2002 most of the UK's electricity industry was in the hands of vertically integrated European companies like E.on, RWE and EDF (the latter of course being controlled by the French state), and by 2005 the total industry spend on R&D in the UK, again across the whole utility sector, was down to £15 million. Nor should we be surprised at this turn of events – the responsibility of the privatized energy companies was not to ensure the long-term security of the UK's energy supply; their responsibility was to their (largely non-UK) shareholders.

By 2005, recognition was growing in the UK government that the extremely low level of R&D effort in energy - both by government and in industry - might not be a good idea. It is probably fair to associate this change to a single individual, Sir David King, who became the UK Government's Chief Scientific Advisor in 2000. King was an outspoken and effective advocate about the dangers of climate change, and the need for more research into energy, and as a result there was a significant rise in government R&D spending. A public-private Energy Technology Institute was set up, and the research councils co-operated on a joint energy research programme. By 2010 this had led to a significant rise in R&D, but a new government and its austerity policy reversed this, with a 23% cut in the cash budget in 2011.

The direction of the UK government's current energy policy is, to be polite, not wholly clear. Painfully slow moves are being made to secure some nuclear new build, the government is hanging back from supporting proposals to implement carbon capture and sequestration at scale, current renewables are facing difficulties of politics and cost, and the issue of climate change has been sidelined. Current scenarios anticipate a substantial increase in electricity generation from gas without carbon capture, while high political hopes are being attached to the development of an onshore shale gas industry.

Some people argue that current sources of renewable energy are too expensive, and a combination of gas and nuclear should be used as a stop-gap while intensive research and development brings forward cheaper and more scalable renewable energy technologies. This argument has some merit, but its proponents need to face the fact that recently we have seen, not an intensification of energy research, but its running down. Securing sustainable energy supplies is without doubt a strategic imperative for governments across the world, but the strategic research needed to support this goal is what the market has singularly failed to deliver.

8. Science policy from Waldegrave to Willetts

As we have seen, the UK has seen a considerable decline in support for applied and strategic science from both government and private sector. The picture for academic science – the basic science carried out largely in universities or Research Council institutes – is somewhat different.

There has been a considerable degree of continuity in Government policy for supporting academic science for more than twenty years, despite changes in government. Policy has asserted the promotion of economic growth as the primary goal of science policy, and has emphasised measures aimed at aligning the supply of basic science and trained scientific manpower to the needs of 'users' of science. Thus we have seen an increasing emphasis on the need to prioritise areas of science endeavour that are believed to support the needs of industry and the introduction of measures to reduce barriers of interaction between academic scientists and users of science in industry. This 'supply side' science policy has produced some positive outcomes – in terms of the quality of its purely scientific outputs, the UK science base is internationally competitive, and this has clearly helped attract overseas business R&D investment. But it is now becoming clear that our deepest problems are at the demand side – it is the shrinking of demand for basic science by those in a position to develop and commercialise it that lies behind some of our current growth problems.

The current era in UK science policy dates to 1993. After more than 10 years of shrinking budgets for science generally, both in government research laboratories and higher education, the science minister in John Major's Conservative government, William Waldegrave, set out a new path in a White Paper *Realising our Potential* (HMG, 1993). This emphasised the importance of economic motivations for doing science, and set out an argument for government funding of science based on the classical notion of market failure – the failure of private-sector inventors to be able fully to capture the benefits of scientific advances. It led to a reformulation of the missions of the research councils to 'make explicit their commitment to wealth creation and quality of life', and called for a breaking down of barriers between those who create science and those in industry who use it. It maintained that private-sector industry was responsible for investing in innovation and bringing new products, and proposed the privatisation of government research establishments, while insisting on the need to increase the supply of science and scientific manpower in areas that emerged as priorities for industry and government.

The election of a Labour government in 1997 led to no fundamental change in direction. Under Lord (David) Sainsbury as Science Minister, the government published a long-term plan for science – the 2004 *Science and innovation investment framework 2004 – 2014* (HM Treasury, 2004). This was based on the same paradigm of correcting market failure. There was some change of emphasis from *Realising Our Potential*, in that there was a recognition that the corporate landscape had changed. While *Realising Our Potential* is characterised by an unarticulated assumption that there was a diverse population of firms in a position to use research, the 10-year Framework recognised that overall business R&D was too low, and acknowledged the existence of a more fluid landscape characterised by the idea of 'open innovation'. Thus it introduced new objectives for the science base, of bringing in inward R&D investment by multinationals, raising the R&D intensity of mid-sized firms, and the foundation of new technology-based sectors through the creation and rapid growth of new enterprises supported by venture capital.

One new dimension of the 10-year Framework was an identification of the need to support interdisciplinary research motivated by societal challenges. This had been driven by the very effective advocacy of the then Government Chief Scientific Advisor, Sir David King, of the need for more research into energy and climate change.

The outcome of the 10-year Framework was several years of real terms increases in the part of the government science budget spent through the research councils, largely in the universities. Spending on science by Government departments and public sector research establishments did not fare so well, however. In effect, there was a transfer of funding from strategic science to basic science. At the same time, though, there was an increasing rhetorical emphasis on the need to connect basic science to economic and other outcomes. This manifested itself in what became known as the 'impact agenda', much to the discomfort of many University based scientists, who interpreted it as an explicit project to change the emphasis of publicly funded science from basic to more explicitly applied directions.

The steady unfolding of long-term economic policies came to an abrupt end with the financial crisis of 2008. Science barely featured in the election of 2010. With formation of a Conservative/Liberal Democrat Coalition built around a perceived need to make rapid reductions in public spending, the lack of any explicit protection for the science budget in the Coalition agreement (in contrast to Health and Education) led to fears that the science budget would be subject to significant cash cuts. As it happened, the headline outcome of the 2010 Comprehensive Spending Review was for a flat cash budget for science (though this looked less favourable when it was realised that the budget for capital had been removed from the science "ring fence" and cut by half).

The new Coalition Government emphasised continuity with the previous government's science policy, with an early speech by the new Science Minister, David Willetts (2010), praising his predecessor: 'Good things were achieved over the past decade and I salute the achievements of David Sainsbury'. Nonetheless, we may now be seeing the beginning of a recognition of the limitations of supply-side science policy. A couple of years later, Willetts (2012) made another speech at which he began to acknowledge the limitations of his earlier point of view. For the first time in many years, the words 'industrial policy' seemed to be speakable once again; this speech called for a strategy for high-technology enterprise. We return to the renaissance of industry policy below.

The success of the 10-year Framework was to be judged by some hard targets. By 2014, the total R&D intensity of the UK economy was to have increased to 2.5% of GDP. Part of this increase was to be obtained by a real terms increase in government science spending, but central to the goal was an anticipated of an increase of business R&D to 1.7%. On the current figures, between 2003 and 2011 total R&D intensity in fact barely shifted, moving from 1.75% of GDP to 1.77%. Business R&D, far from increasing to 1.7% of GDP, actually fell from 1.12% to 1.09%. Supply-side science policy has failed.

9. The re-emergence of industrial policy

Industrial policy fell definitively out of fashion in the Thatcher revolution; the free market orientation of government thinking had no room for selective interventions in particular industrial sectors, while those parts of the economy that were directly controlled by the state were progressively privatized. Rhetorically, industrial policy was associated with the difficulties of the 1970s and the experience of state-owned companies like British Leyland. The industrial policy of the Conservative Governments between 1979 and 1997 was not to have an industrial policy.

The New Labour government elected in 1997 essentially accepted the free market-oriented economic settlement established by earlier Conservative governments. This included a reluctance to make industrial sector-based interventions and a continuation of privatization. New Labour did introduce one new policy that did lead to some more active intervention in industrial sectors, in a way that was perhaps not wholly anticipated. This was the introduction of devolved government in Scotland and Wales, and the establishment of Regional Development Agencies in England. These bodies interpreted their mandate to promote economic growth in the regions and devolved territories in a way that included the promotion of innovation in a sector-specific way.

Meanwhile, in central government various relatively small-scale innovation programmes that continued in the Department of Trade and Industry were gathered together under the auspices of an advisory board – the Technology Strategy Board (TSB) – in 2004. In 2007 the TSB was established as a free-standing agency, based in Swindon, using a budget of order a few hundred million to support a mixture of collaborative grants with industry and networking activities. The underlying philosophy was to use its limited funds to correct identified market failures, rather than to establish any physical infrastructure.

The financial crisis of 2008 did lead to some rethinking of the desirability of the degree of financialisation undergone by the UK economy. Peter Mandelson returned to government as Business Secretary; he set a new tone reflected in a 2009 document, 'New Industry New Jobs' (DBERR, 2009), which stated that the 'the Government has decided to strengthen its own industrial policies'. A report commissioned from the technology entrepreneur and venture capitalist Hermann Hauser(2010) recommended an expanded role for TSB. This included the establishment of physical Technology and Innovation Centres, carrying out translational research and development in partnership with industry, and partially modelled on Germany's Fraunhofer Centres.

The formation of the Conservative/LibDem Coalition after the 2010 led initially to a hiatus in this evolution of an industrial policy. The Coalition Agreement discussed the possibility of implementing the Dyson report (2010), a Conservative Party document which, amongst a number of supply-side measures, also called for public/private translational research institutes.

Meanwhile, the Regional Development Agencies were summarily abolished with little regard for the innovation activity they had supported.

The Minister with responsibility for innovation, David Willetts, initially favoured a supply-side approach to industrial policy based on promoting clusters and developing absorptive capacity for technology. David Willetts's views have evolved – he made a speech directly endorsing industrial policy as more traditionally understood in early 2012 (Willetts, 2012) and the Business Secretary, Vince Cable, outlined a new framework for industrial policy later that year. This is based both on technologies and industrial sectors (with a certain amount of confusion between the two). The full details of how these will be implemented have not yet emerged, but Technology and Innovation Centres (now called Catapult Centres) are being established in a number of technology areas.

10. Science policy and political ideology

The recent broad cross-party consensus on science policy might tempt one to think that questions of the funding of science are broadly apolitical and unconnected with broader questions of political ideology. Taking a longer view, though, one finds that debate about science policy in the past has been deeply entangled with some of the central issues of political debate in the twentieth century.

The defining event in setting the context for modern science policy, in the UK and elsewhere, was the Second World War. Shortly before the war, in the context of the crisis of capitalism and the rising profile amongst some British intellectuals of socialism, Marxism and an admiration for the Soviet Union, a group of publicly prominent left-wing scientists was making the case that the national scientific enterprise should be planned and directed towards solving the problems of society (Werskey, 1978). The most coherent statement of this position was made by the Marxist crystallographer J.D. Bernal in his book The Social Function of Science (Bernal, 1939).

The central planning of science, then, was seen as an integral part of the central planning of economies. The case against central planning in general was forcefully made by Friedrich Hayek, and it was Hayek's friend and intellectual ally, the chemist Michael Polanyi, who was most vocal in opposing the case made by Bernal and his allies for the planning and direction of science (Polanyi, 1951). Polanyi insisted on the strict division between pure science and applied science, extending Hayek's arguments about the market as a mechanism for integrating dispersed knowledge to argue that the scientific community acted as a market place for ideas - 'the pursuit of science by independent self-co-ordinated initiatives assures the most efficient possible organization of scientific progress. And we may add, again, that any authority which would undertake to direct the work of the scientist centrally would bring the progress of science virtually to a standstill' (Polanyi, 1962).

These intellectual debates, however, were eclipsed by the events of the Second World War. The combination of directed and planned science and industrial-scale technology development led to the rapid development of new military technologies like radar and the atomic bomb. As the Cold War emerged seamlessly from the end of the Second World War, new technologies like the ballistic missiles, the jet engine, chemical and biological weapons and the hydrogen bomb required even greater direction of science and technology. Thus the UK ended up with a planned and directed scientific and technological establishment on a huge scale (Edgerton, 2005), but one developed by military engineers and capitalist chemists rather than by Bernal's circle of socialist scientists.

The post-war year saw Bernal and his circle marginalised; his continuing enthusiasm for the Soviet Union lost him influence, as the true nature of Stalin's rule became clear and the Lysenko episode, in which the full force of a totalitarian state was used to back the wrong side in a scientific dispute about evolution, illustrated the dangers of too close an alliance between government and the operation of science. Polanyi's views, were, on the other hand, explicitly used in the ideological struggles of the Cold War. They founded a myth – the independent republic of science – that was and remains enormously attractive to the world of elite academic science. This view of science, however, remained remarkably silent on one crucial question: who is going to pay for pure science, and why would they?

The answer to this question had been suggested in an influential document from the USA – Science: The Endless Frontier (Bush, 1945). Vannevar Bush, Director of the US Office of Scientific Research and Development, resolved the apparent dilemma of the need to leave the direction of research to emerge from the creativity of individual gifted scientists, while still harnessing the overall research effort to meet national goals. To Bush, it was clear why the state should support science – to meet three broad goals: to fight disease, to increase national security through the development of new weapons, and to provide jobs and economic growth through the development of new products and new industries. But, paradoxically, these goals were to be best achieved by supporting 'the free play of free intellects', engaged in 'basic science'. Basic scientists do not and should not consider the potential applications of their work, but applications will surely emerge from basic science, and the nations that support the basic science will gain economic rewards.

Nonetheless, Bush was clear that basic science, carried out mostly in University laboratories, was likely to be a minor fraction of the overall research and development enterprise, creating a reservoir of new knowledge and trained people to be drawn on by this much wider, more applied, activity. He noted that in 1940 spending on applied research carried out by industries and government was a factor of ten greater than that on university research - 'most research conducted within governmental laboratories is of an applied nature. This has always been true and is likely to remain so'. His concern was to justify an increase in state spending on basic research and to propose an agency to manage this. This was to come to pass as the National Science Foundation.

In the UK, the research and development landscape of the post-war warfare state comprised military laboratories, the Atomic Energy Authority carrying out both military and civil nuclear research, and the laboratories of nationalized industries, such as the Central Electricity Generating Board and the Post Office (later to become British Telecommunications). Industrial combines such as BAC, GEC and ICI operated in high technology sectors such as aerospace, electronics and chemicals, and supported large corporate laboratories. There were close links between scientists in the civil and military public sector research laboratories, the public and private corporate laboratories and the universities.

The winding up of this corporatist innovation state began in 1979 with the election of the Conservative government under Margaret Thatcher. The growing influence of free market economics through the 1970s on Thatcher through organizations like the Centre for Policy Studies is well known. It is also widely known that Thatcher, unusually for a senior British politician of any party, had a science degree (in chemistry) and some research experience of her own. However, little comment has been made, until a recent article (Agar, 2011) about the influence of Thatcher's personal experience of science on the evolution of science and innovation policy in her own government.

A defining event was the publication, in 1972, of a government Green Paper – A Framework for Government Research and Development (for a contemporary review, see Dobbs, 1972). This actually contained two independent reports, one by Lord Dainton, and a more notorious one by Lord Rothschild. The Rothschild report argued that applied research should be carried out on a 'customer-contractor' basis. For example, the Ministry of Agriculture, Fisheries and Food (MAFF) might decide what agricultural research national need demanded, and it would then contract with the Agricultural Research Council for that research to be supplied, with the agreed price being transferred from the MAFF budget to the research council. These suggestions were strongly resisted by the Royal Society and many senior scientists as amounting to an unwarranted infringement of the autonomy of science by politicians.

The Minister in charge of the science budget at the time of the Rothschild report was Margaret Thatcher. Since Thatcher's practical experience of science was in the commercial world – in the plastics company BX and the food company J. Lyons – she, perhaps, was particularly resistant to any notions of a special status, outside the market, for science. So her adoption of the principle that science, too, could be marketised, should not be a surprise.

11. Market failure or failure of markets – can a free market deliver radical innovation?

If we focus, not on science, but on innovation more generally, the role of the free market seems at first clearer. To many observers, technology is a force that cannot be steered; it evolves in response to the demands of the market, which provides the only effective way of incorporating public preferences into decisions about technology development. Technology, in this view, is an autonomous agent that unfolds with a logic akin to that of Darwinian evolution. This view, widely held amongst the technological elite of Silicon Valley, is very eloquently expressed in a recent book by Kevin Kelly (2010). The origin of this view can also be traced to Friedrich Hayek's arguments against the 1940s vogue for central planning.

Hayek's argument against planning rests on two insights (see especially Hayek, 1945). Firstly, he insists that the relevant knowledge that would underpin a rational planning of an economy or a society is not limited to scientific knowledge, and must include the tacit, unorganized knowledge of people who are not experts in the conventional sense of the word. This kind of knowledge, then, cannot rest solely with experts, but must be dispersed throughout society. Secondly, he claims that the most effective - perhaps the only - way in which this distributed knowledge can be aggregated and used is through the mechanism of the market. If we apply this kind of thinking to the development of technology, we are led to the idea that technological development would happen in the most effective way if we simply allow many creative entrepreneurs to try different ways of combining different technologies and to develop new ones on the basis of existing scientific knowledge and what developments of that knowledge they are able to make. When the resulting innovations are presented to the market, the ones that survive will, by definition, the ones that best meet human needs. Stated this way, the connection with Darwinian evolution is obvious.

This is a very coherent and seductive position. The difficulty with it is that an examination of the recent history of technological innovation presents a very different picture. The technologies that made the modem world - in all their positive and negative aspects - are overwhelmingly the result of the exercise of state power, rather than of the free enterprise of technological entrepreneurs. New technologies were largely driven by large-scale interventions by the technologically advanced and militarily focused states that dominated the twentieth century. The military-industrial complexes of these states began long before Eisenhower popularized this name, and existed not just in the USA, but in Wilhelmine and Nazi Germany, in the USSR, and in the UK. At the beginning of the century, for example, the Haber-Bosch process for fixing nitrogen was rapidly industrialized by the German chemical company BASF; however, the importance of this process for producing the raw materials for explosives ensured that the German state took much more than a spectator's role. Smil (2000) quotes an estimate for the development cost of the Haber-Bosch process of US$100 million at 1919 prices (roughly US$1 billion in current money, equating to about $19 billion in terms of its share of the economy at the time), of which about half came from the government of the Second Reich. The importance of the Haber-Bosch process can hardly be overstated – the ability to use fossil fuels to fix nitrogen removed the constraints on food production imposed by the natural nitrogen cycle, was directly responsible for the world's population growth in the twentieth century, and made possible the very large increases in the yields of food crops of the 'Green Revolution'.

One of the most important more recent examples is the role of state spending in creating the modern information technology industry. Computers have been closely bound up with governments and the military throughout their history. The first programmable electronic computer was Colossus – developed by the UK's Government Code and Cypher School to break codes in the Second World War. The Internet emerged from work supported by the US defence research funding agency DARPA, as a robust distributed communications network. The Global Position System, which provides location and timing services to smart phones, computers and navigation devices, was a US military project and remains under the ownership and control of the US government. Mazzucato (2013) nicely illustrates the dependence of IT companies on technologies developed by what she calls the 'Entrepreneurial State' by identifying the government origins of the technologies currently exploited in the very successful products of Apple. This line of argument should not taken to imply that the innovative contributions of companies like Apple in turning these technologies into highly functional and novel products are to be underestimated; the point is that it is these underlying state-sponsored technologies that make possible at all the impressive and significant innovation of private-sector IT companies.

Of course, the historical fact that the transformative, general-purpose technologies that were so important in driving economic growth in the twentieth century emerged as a result of state sponsorship does not by itself invalidate the Hayekian thesis that innovation is best left to the free market. To understand the limitations of this picture, we need to return to Hayek's basic arguments. Under what circumstances does the free market fail to aggregate information in an optimal way? Markets fail to deliver radical innovation because people are not always rational economic actors - they know what they want and need now, but they are not always good at anticipating what they might want if things they cannot imagine become available, or what they might need if conditions change rapidly. There is a natural cognitive bias to give more weight to the present, and less to an unknowable future. Just like natural selection, the optimization process that the market carries out is necessarily local, not global.

This means that the free market works well for evolutionary innovation - local optimization is good at solving present problems with the tools at hand now. But it fails to be able to mobilize resources on a large scale for big problems whose solution will take more than a few years. So, we would expect market-driven innovation to fail to deliver whenever timescales for development are too long, or the expense of development too great. As we have seen above, the recent experience of the UK shows that the private sector rejects long-term investments in in infrastructure and R&D, even if the net present value of those investments would be significantly positive.

The contrast is clear if we compare two different cases of innovation - the development of new apps for the iPhone, and the development of innovative new passenger aircraft, like the composite-based Boeing Dreamliner and Airbus A350. The world of app development is one in which tens or hundreds of thousands of people can and do try out all sorts of ideas, a few of which have turned out to fulfill an important and widely appreciated need and have made their developers wealthy. This is a world that is well described by the Hayekian picture of experimentation and evolution - the low barriers to entry and the ease of widespread distribution of the products rewards experimentation. Of course, it is crucial to remember that the information technology platforms, which enable this innovation, would not themselves have been possible without state investment (Janeway, 2013).

Making a new airliner, in contrast, involves years of development and outlays of tens of billions of dollars in development cost before any products are sold. Unsurprisingly, the only players are two huge companies - essentially a world duopoly - each of whom is in receipt of substantial state aid of one form or another.

The lesson is that technological innovation does not just come in one form. Some innovation - with low barriers to entry, often building on existing technological platforms - can be done by individuals or small companies, and can be understood well in terms of the Hayekian picture. But innovation on a larger scale, the more radical innovation that leads to new general-purpose technologies, needs either a large company with a protected income stream or outright state action. In the past the companies able to carry out innovation on this scale would typically have been a state sponsored 'national champion', supported perhaps by guaranteed defense contracts, or the beneficiary of a monopoly or cartel, such as the postwar Bell Labs in the USA or ICI in the UK.

Opponents of the idea of large-scale state innovation invariably will cite costly failures, such as Concorde and the UK nuclear programme. Undoubtedly some state-sponsored innovation has led to large scale and costly failures, and there are hard lessons to be learnt from these. But we should beware a 'failure bias' when talking about public sector-led innovation – innovations that have succeeded (such as the Internet) become fully assimilated into the private sector and their origins in government are easily forgotten or obscured.

Conventional innovation theory talks about the way in which the state can intervene to promote innovation by correcting market failure. But the lesson from the history of the radical innovations that shaped the twentieth century is that many of them arose as a result of state interventions on scales going well beyond simple correction of market failure. In some cases, for example the Haber-Bosch process, the market for the innovation was obvious, but the scale of the effort required to bring it about was beyond what the private sector could undertake by itself. In other cases, such as the Internet, state action brought about the innovation to fulfill some strategic purpose of its own, and then entirely new and unforeseen applications for the innovation, once invented, were subsequently developed through a Hayekian process of private sector trial and subsequent market testing. In neither case does it seem sufficient to describe the process as a simple correction of market failure; instead, it underlines the failure of markets alone to develop truly radical innovations.

12. Accelerating change or innovation stagnation?

The idea that technological progress is getting faster and faster is an article of faith for many. At the extreme end of this point view are futurists such as Ray Kurzweil (2005), who regard the exponential growth of computing power summarized in Moore's Law as just one example of a general law of accelerating technological change, shortly to lead to a profound discontinuity in human history, the technological singularity. On the other hand, we have begun to see economists like Tyler Cowen (2011) and Robert Gordon (2012) drawing our attention to the possibility that innovation, far from accelerating, is currently stagnating. They refer to an argument made by technology historians David Edgerton (2006) and (in considerable detail) Vaclav Smil (2005,2006) about the relative lack of importance of recent developments in information technology, in comparison with the truly world-changing effects of the new technologies of the late nineteenth and early twentieth century – such as electricity, telephones, internal combustion engines and the Haber-Bosch process.

A slightly different, but not unrelated argument, points to the discovery of sources of cheap, concentrated fossil fuel energy as being the ultimate source of all the remarkable economic growth of the last 250 years (Ryan and McKevitt, 2013). This view, at its most pessimistic, regards modern industrial society as a transient consequence of our ability to use fossil fuels to escape temporarily our resource limitations (Grantham, 2011). As remaining stocks of fossil fuels become harder and more expensive to extract, and the effects of climate change that result from the accumulated emissions of carbon dioxide from fossil fuel use become more severe, economic growth and technological progress will be more difficult to sustain.

The main plank of the case for accelerating technological change is the observation that the number of transistors on an integrated circuit has, since their invention in 1958, roughly doubled every two years. This is commonly given the status of a 'law' – 'Moore's Law' – though arguably it is better thought of as a self-fulfilling prophecy, a guide to mobilize and coordinate the research and development of the many different actors in this industry. This kind of exponential growth is neither unique nor unprecedented in the history of technology (Lienhard, 1985); the efficiencies of steam engines in the nineteenth century followed a similar law, albeit with a much slower time-constant. Of course, this exponential progress came to an end as the physical limits imposed by the second law of thermodynamics were approached. Similarly, Moore's law will run its course sooner or later as well, either as the physical limits imposed by the discrete size of atoms make their effects felt, or because economics puts a limit on the increasing size of financial investments necessary to create ever more closely packed circuits.

Can we resolve the apparent discrepancy between the idea of ever-accelerating technological change and the suspicion that innovation may, in some ways, be stagnating? The key point is that "technology" is not a single thing, which can be described by a single rate of change, be that is fast or slow. There are many different technologies, and at any time some may be advancing fast, some may be advancing more slowly, some may be in stasis, and some may even be regressing.

At the moment, it may be helpful to think of three realms of technological innovation. We have the realm of information, the material realm, and the realm of biology. In these three different realms, technological innovation is subject to quite different constraints, and has quite different requirements.

It is in the realm of information that innovation is currently taking place very fast. This innovation is, of course, being driven by a single technology from the material realm – the microprocessor. The characteristics of innovation in the information world is that the infrastructure required to enable it is very small; a few bright people in a loft or garage with a great idea genuinely can build a world-changing business in a few years. But the apparent weightlessness of this kind of innovation is of course underpinned by the massive capital expenditures and the focused, long-term research and development of the global semiconductor industry, with its roots in the military interests of the US state.

In the material world, things take longer and cost more. The scale-up of promising ideas from the laboratory needs attention to detail and the continuous, sequential solution of many engineering problems. This is expensive and time-consuming, and demands a degree of institutional scale in the organizations that do it. A few people in a loft might be able to develop a new social media site, but to build a nuclear power station or a solar cell factory needs something bigger. The material world is also subject to some hard constraints, particularly in terms of energy. And the penalties for making mistakes in a chemical plant or a nuclear reactor or a passenger aircraft have consequences of a seriousness rarely seen in the information realm.

Technological innovation in the biological realm, as demanded by biomedicine and biotechnology, presents a new set of problems. The sheer complexity of biology makes a full mechanistic understanding hard to achieve; there is more trial and error and less rational design than one would like or is sometimes admitted to. Living things and living systems are different and fundamentally more difficult to engineer than the non-living world; they have agency of their own and their own priorities. So they can fight back, whether that is pathogens evolving responses to new antibiotics or organisms reacting to genetic engineering in ways that thwart the designs of their engineers. Technological innovation in the biological realm carries high costs and very substantial risks of failure, and it is not obvious that we have the right institutions to handle this. One manifestation of these issues is the slowness of new technologies like stem cells and tissue engineering to deliver, and we are now seeing the economic and business consequences in the unfolding crisis of innovation in the pharmaceutical sector that we discussed above.

Digital innovation - innovation in the realm of information - is important, but it is not, by itself, enough. Ultimately, of course, it depends on material innovation – we would not have iPhone apps if someone had not first invented and developed touchscreens. So if material innovation slows down, then, some time later, so will digital innovation. Innovation in the material realm also underpins the development of new energy sources, on which our entire economy depends. Innovation in manufacturing takes place in the material realm; Pisano and Shih (2009) argue that a prosperous economy depends on a healthy 'industrial commons', the networks of skills and innovative capacity that underlie the infrastructure of suppliers and top-tier manufacturers that constitute flourishing industry clusters. Our abiding need to heal the sick means that we will always need to intervene in the biological realm. Digital innovation can assist innovations in the material and biological realms, but ultimately we cannot escape the fact that we live in the material world. We need innovation in all three realms – the digital, the material and the biological – and fast progress in one realm cannot fully compensate for slower progress in the other areas.

But by trusting innovation to the market we end up concentrating on innovation in the realm of information, because only there can we hope to make financial returns on the rapid timescales demanded by the short-term horizons of the market. The rapid pace of innovation in the realm of information has obscured much less rapid growth in the material realm and the biological realm. It is in these realms that slow timescales and the large scale of the effort needed mean that the market seems unable to deliver the innovation we need.

The economist Tyler Cowen (2011) discusses the slow-down in innovation in the context of the USA with a metaphor - that we have already taken all the 'low-hanging fruit' of innovation. As a metaphor, this is a rather bad one; the innovation of the twentieth century – far from representing 'low hanging fruit' – was the product of a large-scale investment of money and manpower in long-term research and development. It is this investment that has, in the last thirty years, slowed down in all areas in the UK. For the important field of energy research, this slowdown has been worldwide.

13. The innovation we want and the innovation we need

Not everyone agrees that we need more technological innovation. At the "deep green" wing of the environmentalist movement, technology and the industrial society it has given rise to are regarded as a problem threatening the planet and its ecosystem. For example, the environmentalist writer Bill McKibben (2003) eloquently makes the case that the technologies we have already are good enough, and new technologies will inevitably cause more problems than they solve. A more important, though less vocal, source of resistance to innovation comes from representatives of incumbent economic interests. Economic theories of innovation make it clear (see e.g. Acemoglu, 2009) that incumbent firms have lower incentives to innovate than new entrants, because the innovation will lower the profits from their existing businesses. The slow response of Kodak to the new digital imaging technologies that undermined, and ultimately destroyed, their film business is a well-known example. More generally, the picture of innovation as involving 'creative destruction', following Schumpeter (1942), stresses that innovation produces losers as well as winners. A political system that gives excessive weight to the voices of the current holders of economic power, who stand to lose by innovation's process of creative destruction, will tend to put a brake on innovation even when it would be beneficial for society as a whole.

At a global level, the argument that we do not need more technological innovation can be quickly disposed of. Humanity is existentially dependent on the technology we have got – perhaps the most graphic example of many is the fact that somewhere between a third and a half of the current population of the earth owe their existence to artificial fertilisers, produced using fossil fuels by the Haber-Bosch process. But we know that the technology we have is not sustainable – our dependence on fossil fuels, if continued indefinitely, will lead both to potentially catastrophic climate change and to escalating costs as the most accessible deposits are exhausted. So we have not got any choice but to develop better ones.

At the national level, the argument for promoting technological innovation is that it leads to productivity gains, and increasing productivity is the only route, for developed countries like the UK, to increased long-term economic growth rates. In the specific circumstances of the UK, with a persistent trade deficit, rapidly depleting oil and gas fields and a financial services industry that needs to get smaller, there is a particular need to improve the competiveness of tradable sectors such as manufacturing.

These general economic arguments relating technological innovation to growth do not specify what type of innovation is involved or in what sectors that innovation might be concentrated. But, as was stressed in the last section, technology is not a single thing that advances at a single pace. Instead, innovation in some areas may be proceeding very fast, while in other areas the pace of change may be much slower. Three broad factors direct technological change – state action, market demand, and the opportunities offered by the current state of science.

In the post-war period in the USA and the UK, state action was motivated by the military requirements of the Cold War. The discoveries of nuclear and solid state physics made possible developments in control systems, electronics and communications technologies, and nuclear and aerospace engineering, on which many of the great industries of the late twentieth century were founded.

In the last twenty years, the market has taken the lead in finding new uses for the electronics, communications, and information technology originally developed by the Cold War military-industrial complex. The driving forces here have been, in essentials, entertainment, advertising and retailing. Considerable innovative energy has been devoted to finding new business models that actually make money, though the reliably lucrative triad of pornography, gambling and loan-sharking have been successful early adopters of the new technologies.

If the driving forces for developing new technologies in recent history have been, first, war, and, then, entertainment and advertising, what should we anticipate as driving forces for technology in the future?

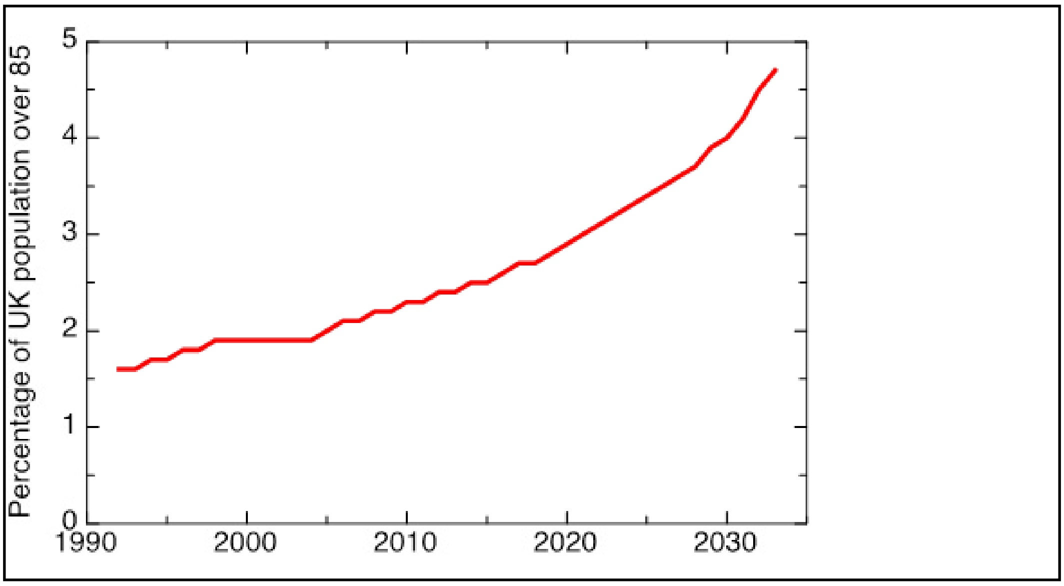

Figure 9: projected fraction of the UK population over 85 in age. Source: ONS (2012)

The universal desire to cure illness has, of course, always been a strong driving force for new medical technology, but changing demographics will lead to new pressures. The UK, like most of the developing world, has an ageing population – population projections suggest that the fraction of the population over 85 years will double in the next twenty years. A widespread increase in life expectancy, itself a product of a variety of twentieth century technological innovations, is greatly to be welcomed. But it does pose a serious challenge to the financial sustainability of our health systems. The demands people place on health systems are concentrated towards the ends of their lives, and the diseases of old age remain intractable. For example, dementias like Alzheimer's disease remain without effective treatment, and condemn increasing numbers of victims and their relatives and carers to great suffering. It is in this very difficult context that the slowdown in innovation in the pharmaceutical industry is particularly worrying.

It is hard to overstate the importance of energy in creating today's industrial economies. In the UK, it was the large-scale use of coal, beginning as early as the seventeenth century, which allowed the economy to escape the constraints of environmental limits. Between 1650 and 1850, the total amount of energy used in England and Wales increased by more than a factor of 25, as coal fuelled the industrial revolution (Wrigley, 2010). More currently, China's rapid development has resulted in an increase in energy use of a similar scale on a much shorter timescale. From 1965 to now, China's energy use has increased by a factor of 20 (BP 2013). In 1965, China used 2/3 of the total energy used by the UK, despite the great disparity in total population; in 2012, it used 13 times more.

Our dependence on fossil fuel energy gives rise to two distinct problems. The first relates to supply. Although plenty of fossil fuels remain to be exploited, the reserves that are most easily and cheaply extracted are running out. Replacement reserves are more difficult to extract – such as tight oil and tar sands – or in more inaccessible places - such as deep offshore on in the Arctic. Meanwhile, the rapid industrialization and development of countries like India and China lead to increased demand. Oil prices are currently as high, in real terms, as they have been since 1864; they are about twice as high as they were in the 1973-4 oil crisis. This is despite a weakening in demand due to the current world economic slowdown. Energy markets are volatile, and prices have dropped back in the past, but this time the increasing production cost of oil will effectively place a floor under the price. High fossil fuel energy prices are less a rent extracted from consumers by producers, as they were in the past, and more a reflection of the increasing amount of real resource that needs to be devoted to getting them out of the ground.

This represents, not just a transfer of wealth, but a real reduction in welfare for all industrial economies.

The second problem is more fundamental. Burning fossil fuels has increased the concentration of carbon dioxide in the atmosphere from less than 300 parts per million in the pre-industrial era to 400 parts per million now. Carbon dioxide is a greenhouse gas; this means that as its concentration increases more of the sun's energy is retained at the earth's surface compared to that which is re-radiated back into space, until a new equilibrium is reached at a higher surface temperature. The earth's climate system is complex, so the precise sensitivity to increased carbon dioxide remains uncertain. What is not in doubt is that the net energy being retained at the earth's surface is increasing, so temperatures will go on rising.

Progress so far in moving to non-fossil fuel sources of energy is illustrated in the figure. For the world as a whole, there was a rise in energy obtained from non-fossil fuel sources from the 1970s to the 1990s, reflecting a build-out of nuclear energy in major energy-using countries. The last decade and a half has seen no further progress in the non-fossil fuel share of energy being used; the introduction of new low carbon energy sources – wind and solar – has not compensated for the continuing increases in fossil fuel consumption. The picture in the UK is more fluctuating – an increase in wind energy and biomass just compensates for loss of nuclear capacity, while oil consumption has fallen due to the lower level of economic activity following the financial crisis. What is clear is that, neither in the UK nor in the world more widely, is there any sign of a rapid transition to a non-fossil fuel based energy economy.

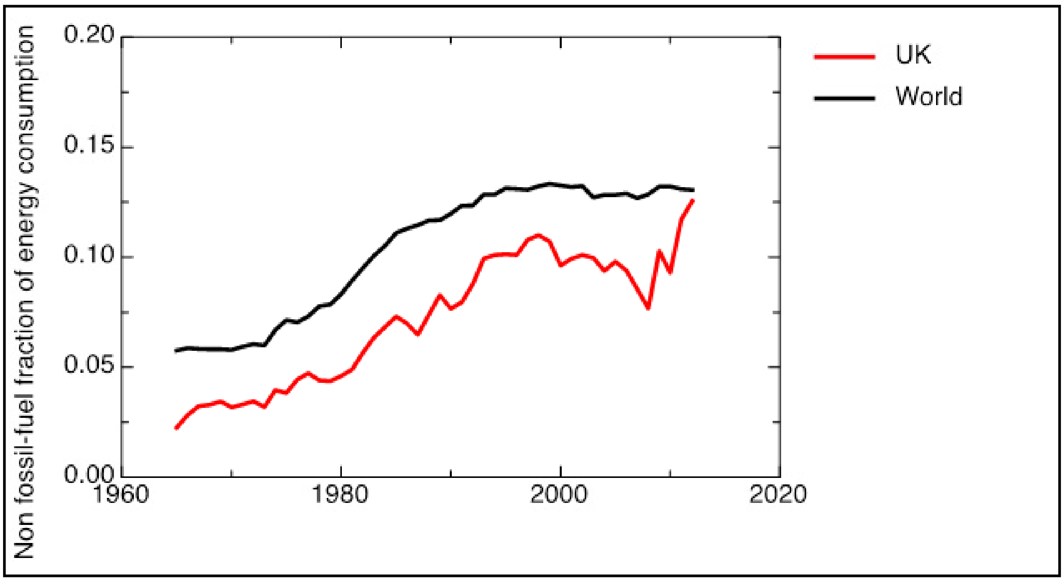

Figure 10: Fraction of primary energy consumption obtained from non-fossil-fuel sources (including nuclear). Data source: BP Statistical Review of World Energy 2013

There is a view that there has been too much emphasis on deploying existing low carbon technologies, perhaps before they are fully mature, rather than in directing an intensive research program to develop better ones that could compete on cost with fossil fuels (Acemoglu et al., 2012). Rather than spending very substantial sums of money subsidizing the current generation of low carbon energy, one could argue that one should achieve some carbon savings by moving from high carbon fossil fuels like coal to lower carbon natural gas, and redeploy money saved by reducing subsidies to current wind and solar in energy research and development. This argument has merit, but there needs to be realism about the scale of the programme that would be required given the worldwide slowdown in energy R&D in the last thirty years, as discussed in section 7. There is a lot of ground to make up.

If the areas of need for innovation are clear, could it be the case that the opportunities that science is providing are drying up? This question is difficult to answer with firm evidence, but my personal view is that it does not seem likely. Here are just two examples of current areas of science with huge potential for applications in the future.

In physical science, the ability to precisely specify the arrangement of atoms and molecules on a nanometer scale in three dimensions allows one in principle to achieve complete control of the interaction of light, electrons and matter. The resulting 'optical metamaterials' currently attract popular attention for their fantasy-like potential to make 'invisibility cloaks'; real applications in imaging, new forms of computing and light harvesting are likely to be less striking but more far-reaching.

In cell biology, the recognition that many biological macromolecules take part in complex information processing networks related to gene regulation and environmental sensing has led to the realisation that one should in some senses think of single biological cells as sophisticated chemical computers. The emerging fields of systems and synthetic biology that have resulted from this insight currently are characterised by as much rhetoric as solid achievement, but that should not obscure the likelihood that such a profound underlying change in perspective will have important practical consequences.

In this picture of technological innovation, the state of current science defines what is possible, while the market says what (some, economically powerful) people want. What happens when the market gives us what we want, but it fails to give us what, arguably, we need for example large-scale, inexpensive sources of low carbon energy? The lesson of previous episodes of profound technological change is that to achieve such change, the state must step in.

14. Intervening to support innovation

It is widely accepted that markets cannot supply the basic scientific research and trained manpower that technological innovation rests on, and our supply side innovation policy has filled this gap. However, it is now clear that this is not enough. Industrial research and development is withering away, and the state has largely withdrawn from applied and strategic research.

Why is the market failing to deliver? The straightforward answer is that applied R&D required to get new technology in the material and biological domains into widespread use at scale is expensive and takes a long time. Capitalists have always had difficulty appropriating the returns from innovation – most of the rewards generated from innovation go to wider society, rather than to their inventors (Nordhaus, 2004). If the investment landscape is driven by short-termism and a focus on immediate returns on capital, then the long-term investment required to generate technological innovation will be squeezed out.

The issue is not that there is insufficient money to invest in R&D; it is that there are other opportunities for investing that money that offer higher returns, at lower risk, on shorter timescales. The problem is that many of these opportunities do not support productive entrepreneurship, which brings new products and services to people who need them and generates new jobs. Instead, to use a distinction introduced by economist William Baumol (1990) they support unproductive entrepreneurship, which exploits sub-optimal reward structures in an economy to make profits without generating real value. Examples of this kind of activity might include restructuring companies to maximize tax evasion, speculating in financial and property markets when the downside risk is shouldered by the government, exploiting privatizations and public/private partnerships that have been structured to the disadvantage of the tax-payer, and generating capital gains which result from changes in planning and tax law.

Current remedies for the lack of private sector investment in R&D are founded on the idea of correcting market failure. They involve giving money to companies, either directly through R&D subsidies, or indirectly through tax concessions such as the R&D tax credit and the "patent box". The difficulties here are the likelihood of dead-weight costs, in which the state supports expenditure that the companies would have made anyway, and the difficulty, in the case of multi-national companies, or retaining benefits in the UK.

There is much rhetorical focus on the role of small companies, which may be supported by the state directly through grants, or through equity investment, or indirectly through the state using procurement to promote innovation. Difficulties here arise through the high cost base and failure to capture economies of scale for small companies, while the lack of large-scale, patient capital makes it difficult to grow companies to the stage where they have significant manufacturing capability. This in turn makes it difficult to gain the benefits of 'learning by doing' and of generating mutually reinforcing clusters of companies in high technology areas. The use of government procurement to support small companies is often talked about, but in practice the aims of driving innovation and achieving value for money come into conflict, with value for money generally winning.

Despite the difficulties, these programmes to support research and development in the private sector undoubtedly have some worthwhile outcomes. However, they do not address the root causes of the problems. If the way our economy is structured rewards unproductive entrepreneurship, then this means that money and effort that should be supporting genuine innovation, to create new products and services that people and society want and need, is unavailable. In short, bad capitalism crowds out good capitalism, and innovation suffers.

Market systems do have one longstanding remedy for the difficulty in appropriately rewarding innovation, and that is the patent system. The patent system is a mechanism by which the state rewards innovation by awarding a time-limited monopoly in the application of the patented invention. The discussion of the pharmaceutical and biotechnology industries in section 6 shows some of the limitations of the system. In a sense, patents, particularly as they are used in the biomedical arena, are both too broad and too short (see e.g. chapter 9 of Nuffield Council for Bioethics, 2012). They are too broad, in that it is possible to make claims over a wide field, thereby inhibiting innovation in neighbouring areas. They are too short, in that, even when a patented invention is successfully commercialised, the period of monopoly is not sufficient to recoup the cost of development and make an appropriate return on this cost.

What the patent system shows is that states have, for many centuries, recognized that the market by itself does not sufficiently reward innovation. The patent system is not, however, the only way this can be done and it may well not be the best way. Cash prizes for innovation, awarded by the state or philanthropists, are another method, which have a long history and are coming back into vogue. The sums in question – typically of order millions of pounds – are ideal for raising publicity but not large enough to pay a return on a substantial research and development program.

The fundamental problem is that the social value of innovations does not usually correspond to their market value, so market incentives, supplemented by a framework of intellectual property rights, do not reward the innovation that society needs. The problem is simply stated, but hard to solve, as it is difficult to create a rigorous framework for judging the social value of innovations. The closest we come to this is in the rise of the idea of 'value-based pricing' for pharmaceuticals, where the price paid for drugs by the NHS is to be determined by a complex formula overseen by the National Institute for Clinical Excellence. It is possible to imagine a system where the social return from a new pharmaceutical is directly estimated and this is used as a basis for rewarding the company that developed it, with the drug being sold at a much lower price reflecting the cost of production, rather than the cost of development.

We can think of this as an example of the state directly commissioning the innovation that society needs. Alternatively, of course, the state could directly create that innovation in its own applied or strategic research organizations, if those were to be recreated. The open question, then, would be how to decide what innovations were needed? One starting point is to create lists of emerging technologies – such as the 'eight great technologies' identified recently by the UK government (Willetts, 2013) - and match these to lists of current challenges.

But how do we choose these problems as the ones for which we most need technological solutions? How do we know that these particular emerging technologies offer the best way of delivering these goals while minimizing the risk of unintended and undesirable consequences? And, given that, by definition, these technologies are still immature, what is the best way of ensuring that they really can make the transition from the laboratory into the real world, to yield their promised benefits and fulfill what are often heady financial predictions for their economic impact? If we get these choices wrong, not only do we suffer from the downsides of inappropriate technologies, we also do not get the benefit of the better technologies we didn't choose. The UK's conventional wisdom is that governments 'can't pick winners'. Caution about the difficulty of making good technology choices is well placed, but often abstaining from making such choices explicitly means that instead choices are made by default as a result of institutional pressures.

The UK government currently does not have the capacity or the recent track record to make these kinds of technology choices. Such choices need to be underpinned by evidence, and will undoubtedly need to be informed by expert advice. But this requires careful thought about the nature of expertise involved. Scientists will be well informed about technical possibilities in their own fields, but are likely to be less informed about the problems of scale-up and commercialization, and run the risk of over-valuing novelty for its own sake. Industrialists bring valuable insights about scale-up and the realities of markets, but may carry biases towards technology incumbents. Evidence will usually be multidisciplinary in character, social factors are likely to be important, and public engagement may often have an important role to make sure that innovations support widely shared societal goals (Nuffield Council for Bioethics, 2012).

In short, the processes for making choices about technologies need to be both rational and democratic. It is important to stress that these are not opposing values – discussions about potential new technologies are implicitly discussions about political values, because they involve different visions of the future. Discussions about technological innovation need to be at the center of a broader political discussion than we currently see happening, one that explores what kind of future people want, and what scale of resources and effort would be required to get there.

15. Taking responsibility for technological innovation and growth

The UK needs more technological innovation, to return the country to sustainable economic growth, and the world needs more technological innovation to solve the big problems we face. The way the UK's political economy is configured is not delivering this innovation, and it will take Government coordination and action to correct this.

Firstly, Government must take responsibility for technological innovation. This means that it must recognized that the market, by itself, will not deliver the technological innovation we need. The state has strategic interests for which Government must take ultimate responsibility. In the twentieth century it was defence that provided the most visible strategic interest, and, as we have seen, the UK built a substantial 'Warfare State' to provide the innovation to meet the demands of a powerful defence establishment. But the postwar settlement also emphasized the responsibility of the state for the health of its citizens, through the NHS, and for economic growth. Both economic growth and more general well-being are underpinned by access to energy. These strategic interests will not be fully met in the future without technological innovation.

It is the Government's responsibility to *create the conditions for technological innovation*. This responsibility has positive aspects that are not controversial; a policy consensus has emphasized the need to maintain the basic science base and ensure a supply of skilled manpower. Government has recognized its role as a broker, making connections and creating forums in which innovative practice can be shared across industry sectors. What governments have not yet recognized enough is that it is not enough to create conditions to *encourage* technological innovation; those conditions that *discourage* technological innovation need to be actively suppressed, or at least not positively favoured. The persistent problems which make it difficult to finance investment, research and development need to be addressed; subsidies, whether explicit or hidden, to activities like real estate and financial services make these problems worse.

Finally, when necessary, accepting responsibility for technological innovation will on occasion mean that Government will need to i*ntervene directly to make technological innovation happen*.

This will mean direct state involvement in applied and strategic research, some of it quite close to application. The areas to be chosen for such interventions will be ones in which there is an urgent strategic need for technological innovation, combined with a manifest failure of the private sector to deliver it. Affordable low carbon energy would be an obvious early candidate.

To return to a question posed at the beginning, some might ask, why should the UK in particular be so concerned about innovation? Innovation happens globally, so why should the UK not wait for someone else to make the technological advances and then reap the benefits? The positive answer is that the UK is in a good position to rebuild its capacity for large-scale technological innovation. The country does retain a good skills base and a strongly performing basic research sector, which gives it an area of comparative advantage that can and should be exploited more. A bleaker answer would highlight the unsustainability of the UK's current growth model. The UK needs to make more tradable goods to replace the exports from declining oil production and an over-sized financial services sector. To do this, the UK needs to build a new developmental state, a state that once again takes responsibility for large-scale technological innovation as the basis for sustainable growth and prosperity.

Notes

1. For example, to return to the 48-79 trend-line by 2020 would require seven years of growth at a wholly unrealistic 6.9% a year.

2. Named after Gordon Moore, founder of Intel.

3. The case against is set out by Henderson (1977), who presents a damning economic case against the UK's Advanced Gas Cooled Reactor programme. However, it would be worth revisiting this analysis, as it compared the UK's AGR program with a hypothetical light water reactor programme, of the kind implemented by the USA, France and Japan. However, the subsequent histories of those light water reactor programmes were marked by considerable cost escalations, even in France (which is often regarded as a model of a successful civil nuclear programme), as detailed by Grubler (2010). Moreover, a consideration of the economic cost of the loss of coolant accidents at Three Mile Island (1979), and much more seriously Fukushima (2011), might well tilt the balance between light water reactors and gas-cooled reactors, which are intrinsically less susceptible to this failure mode.

References

Acemoglu, D. (2009). *Introduction to Modern Economic Growth*. Princeton: Princeton University Press.

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The Environment and Directed Technical Change. *American Economic Review* 102: 131–166.

Agar, J. (2011). Thatcher, Scientist. *Notes & Records of the Royal Society* 65: 215-232.

Baumol, W.J. (1990). Entrepreneurship: Productive, unproductive, and destructive, *Journal of Political Economy* 98: 893-921.

Bernal, J. D. (1939). *The Social Function of Science*. London: Routledge.

BP (2013). BP Statistical Review of World Energy. Available at: http://www.bp.com/en/global/corporate/about-bp/statistical-review-of-world-energy-2013.html

British Venture Capital Association (2013). Private Equity and Venture Capital Report on Investment Activity 2012, May 2013. Available at: http://admin.bvca.co.uk/library/documents/RIA_2012.pdf

Bush, V. (1945). Science, The Endless Frontier, Report to the President, July 1945. Available at https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm

Cable, V. (2012). Industrial Strategy: Cable outlines vision for future of British industry, Speech, 11 Sept 2012. Available at: https://www.gov.uk/government/speeches/industrial-strategy-cable-outlines-vision-for-future-of-british-industry

Card D. and Freeman R.B. (2002). What have two decades of British economic reform delivered? *NBER Working Paper* No. 8801. http://www.nber.org/papers/w8801

Cecchetti, S. G., & Kharroubi, E. (2012). Reassessing the impact of finance on growth. *Bank for International Settlements Working Papers* 381 http://www.bis.org/publ/work381.pdf

Cowen, T. (2011). *The Great Stagnation: How America Ate All the Low-Hanging Fruit of Modern History, Got Sick, and Will (Eventually) Feel Better.* New York: Penguin eSpecial.

Department of Business, Enterprise, and Regulatory Reform (2009). New Industry, New Jobs. Available at: http://www.berr.gov.uk/files/file51023.pdf

Department for Business, Innovation and Skills (2011). Innovation and research strategy for growth, Economics Paper 15: 1–162. Available at: http://www.bis.gov.uk/assets/biscore/innovation/docs/e/11-1386-economics-innovation-and-research-strategy-for-growth

Dobbs, E.R. (1972). The Organisation and Control of Scientific Research by the United Kingdom Government. *Higher Education Quarterly* 1: 345-355.

Dyson, J. (2010). Ingenious Britain: Making the UK the leading high tech exporter in Europe. Conservative Party. Available at: http://goo.gl/hqPCpB.

Edgerton, D.G. (2005). *Warfare State*. Cambridge: Cambridge University Press.

Edgerton, D.G. (2006). *The Shock of the Old: Technology and Global History since 1900*. London: Profile.

European Commission Joint Research Centre (2012). EU Industrial R&D Investment Scoreboard 2012: Available at: http://iri.jrc.ec.europa.eu/docs/scoreboard/2012/SB2012.pdf

Hayek, F. (1945). The use of knowledge in society. *American Economic Review* 35: 519-30.

Gordon, R.J. (2012). Is U.S. Economic Growth Over? Faltering Innovation Confronts the Six Headwinds. *NBER Working Paper* No. 18315. http://www.nber.org/papers/w18315

Grantham, J. (2011). Time to Wake Up: Days of Abundant Resources and Falling Prices Are Over Forever. *GMO Quarterly Letter* April 2011. www.gmo.com

Grubler, A. (2010). The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy* 38: 5174.

Haldane, A. (2011), May 10). The Short Long. Bank of England Speech May 10 2011. Available at: http://www.bankofengland.co.uk/publications/Documents/speeches/2011/speech495.pdf

Hauser, H. (2010). The Current and Future Role of Technology and Innovation Centres in the UK, Department of Business, Innovation and Skills.

Helm, D. (2004). *Energy, the State and the Market: British Energy Policy since 1979.* Oxford: Oxford University Press.

Henderson, P. D. (1977). Two British Errors: Their Probable Size And Some Possible Lessons. *Oxford Economic Papers* 29: 159-205.

HMG White Paper (1993). Realising our Potential: a Strategy for Science, Engineering and Technology, May 1993.

HM Treasury (2004). Science and innovation investment framework 2004 – 2014, July 2004.

Hopkins, M.M., Martin, P.A., Nightingale, P. et al. (2007). The myth of the biotech revolution: An assessment of technological, clinical and organisational change. *Research Policy* 36: 566-589.

Hughes, A., & Mina, A. (2012). The UK R&D Landscape, 1–44. UK Innovation Research Centre (2012). Available at: http://ukirc.ac.uk/object/report/6403/doc/CIHE_1203RDlandscap.pdf

International Energy Authority (2013). R&D Statistics. Available at http://www.iea.org/statistics/RDDonlinedataservice/

Janeway, W.H. (2013). *Doing Capitalism in the Innovation Economy.* Cambridge: Cambridge University Press.

Kay, J., (2012). The Kay Review of UK equity markets and long term decision making, July 2012, Dept of Business, Innovation and Skills. Available at: http://bis.gov.uk/assets/biscore/business-law/docs/k/12-917-kay-review-of-equity-markets-final-report.pdf

Kelly, K. (2010). *What Technology Wants*. New York: Viking.

Kurzweil, R. (2005). *The Singularity is Near: When Humans Transcend Biology,* New York: Viking Penguin.

Lienhard, J. H. (1985). Some ideas about growth and quality in technology. *Technological Forecasting and Social Change* 27: 265-281.

LaMattina, J. L. (2011). The impact of mergers on pharmaceutical R&D. *Nature Reviews Drug Discovery* 10: 559-560.

McKibben, B. (2003). *Enough: staying human in an engineered age.* New York: Times Books.

Mazzucato, M. (2013). *The Entrepreneurial State.* London: Anthem Press.

Nemet, G.F. and Kamman, D.M. (2007). U.S. Energy Research and Development: Declining investment, increasing need, and the feasibility of expansion. *Energy Policy* 35: 746-755.

NESTA (2009). The Innovation Index: measuring the UK's investment in innovation and its effects, November 2009. Available at: http://www.nesta.org.uk/library/documents/innovation-index.pdf

Nordhaus, W.D. (2004). Schumpeterian Profits in the American Economy: Theory and Measurement. *NBER Working Paper* No. 10433. http://www.nber.org/papers/w10433

Nuffield Council for Bioethics (2012). Emerging Biotechnologies: technology, choice and the public good. http://www.nuffieldbioethics.org/emerging-biotechnologies

Office of National Statistics (2011). Statistical bulletin: Business Enterprise Research and Development. Available at: http://www.ons.gov.uk/ons/rel/rdit1/bus-ent-res-and-dev/2011/stb-berd-2011.html

Office of National Statistics (2012). Ageing in the UK Datasets, 2011 Pension Act and 2012 (N.I) Pension Act Update. Available at: http://www.ons.gov.uk/ons/publications/re-reference-tables.html?edition=tcm%3A77-285429

Pisano, G.P., and Shih, W.C. (2009). Restoring American Competitiveness. *Harvard Business* Review 87: 114-125.

Polanyi, M. (1951). *The Logic of Liberty.* London: Routledge & Kegan Paul.

Polanyi, M. (1962). The Independent Republic of Science. *Minerva* 1:54-74.

Ryan, A.J., McKevitt, S. (2013). *Project Sunshine.* London: Icon Books.

Scannell, J. W., Blanckley, A., Boldon, H. et al. (2012). Diagnosing the decline in pharmaceutical R&D efficiency. *Nature Reviews Drug Discovery* 11: 191-200.

Schumpeter, J.A. (1942). *Capitalism, Socialism and Democracy.* New York: Harper.

Smil, V. (2000). *Enriching the Earth.* Cambridge: MIT Press.

Smil, V. (2005). *Creating the 20th century: technical innovations of 1867-1914 and their lasting impact.* Oxford: Oxford University Press.

Smil, V. (2006). *Transforming the 20th century: Technical innovations and their consequences.* Oxford: Oxford University Press.

Smith, G., Akram, M. S., Redpath, K., & Bains, W. (2009). Wasting cash—the decline of the British biotech sector. *Nature Biotechnology* 27: 531–537.

Tomlinson, J. (1996). Inventing 'Decline': The Falling behind of the British Economy in the Postwar Years. *The Economic History Review* 49: 731-757.

Watson, M., and Hay, C. (1998). In the dedicated pursuit of dedicated capital: Restoring an indigenous investment ethic to British capitalism. *New Political Economy* 3: 407-426.

Werskey, G. (1978) *The Visible College.* London: Allen Lane.

Willetts, D. (2010). Science, Innovation and the Economy, Speech at the Royal Institution, 9 July 2010. Available at: https://www.gov.uk/government/speeches/science-innovation-and-the-economy--2

Willetts, D. (2012). Our Hi-Tech Future, Speech at Policy Exchange, 4 January 2012. Available at: https://www.gov.uk/government/speeches/our-hi-tech-future--2

Willetts, D. (2013). Eight Great Technologies, Policy Exchange. Available at:http://www.policyexchange.org.uk/publications/category/item/eight-great-technologies

Wrigley, E.A. (2010). *Energy and the English Industrial Revolution,* Cambridge: Cambridge University Press.

The University Of Sheffield.

Sheffield Political Economy Research Institute
Interdisciplinary Centre of the Social Sciences
219 Portobello
Sheffield S1 4DP

T: +44 (0)114 222 8346
E: speri@sheffield.ac.uk