Eight Great Technologies

Policy Exchange

David Willetts

Eight Great Technologies

David Willetts

Policy Exchange

Policy Exchange is the UK's leading think tank. We are an educational charity whose mission is to develop and promote new policy ideas that will deliver better public services, a stronger society and a more dynamic economy. Charity Registration Number 1096300.

The authority and credibility of our research is our greatest asset. Our research is independent and evidence-based, and we share our ideas with policymakers from all sides of the political spectrum. Our research is strictly empirical and we do not take commissions. This allows us to be completely independent and make workable policy recommendations.

Published by
Policy Exchange, Clutha House, 10 Storey's Gate, London SW1P 3AY
www.policyexchange.org.uk

ISBN: 978-1-907689-40-6

Printed by Heron, Dawson and Sawyer
Designed by Soapbox, www.soapboxcommunications.co.uk

Contents

About the Author

The Rt Hon David Willetts MP is Minister for Universities and Science.

He has been the Member of Parliament for Havant since 1992 and previously worked at HM Treasury and the Number 10 Policy Unit. He served as Paymaster General in the last Conservative Government.

He has written widely on economics and social policy. His book *The Pinch: How the Baby Boomers Took Their Children's Future – And Why They Should Give It Back* was published in 2010.

Foreword

Politicians of all parties have talked about the importance of rebalancing the economy. This means two things – first, ensuring that the economy does not become over-dependent on one sector and, secondly, that the economic divide between North and South should be narrowed.

Science policy has a crucial role to play in both elements of rebalancing and in ensuring that the UK is able to compete in the future in a highly competitive global marketplace.

Now is the right time to ask what the role of government might be in making the most of our comparative and competitive advantages and ensuring that the British manufacturing sector and British business generally gets stronger and can compete on a global scale.

Government policy can play an important role in making this happen, whether it is encouraging research and development, facilitating local or regional clusters or creating a dedicated vocational and technical track in education to ensure that our education system is producing young people with the skills that industry needs.

Helping the UK become world leaders in certain technologies through our expertise in specific areas of research and development could help boost our exports and drive economic growth.

Science policy will be crucial to ensuring the future prosperity of the UK and revived prosperity in towns and cities often left behind in recent decades. And government can play a role in making this happen, without falling back on the old, failed, policies of 'picking winners'.

In this paper, David Willetts makes an important contribution to this debate – setting out eight great technologies in which Britain is

or can be global leaders. They are all exceptional examples of how government can play a role in a new, high technology industrial revolution.

David Skelton, Acting Director, Policy Exchange

1. Introduction: the Funding Framework

Britain has a great scientific tradition. We can sustain that and make Britain the best place in the world to do science.

World-class science is worthwhile in itself. Scientific enquiry embodies the creative power of the human intellect. This blue skies research is defined as "experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts without any particular application or use in view". (OECD Frascati definition). It goes back to the deep human need to make sense of our world.

British scientific excellence is something we can be proud of: it is one of our great contributions to the modern world. Like other highly developed nations, the UK provides public funding for science and research because the benefits are so large and spread widely: businesses and individuals cannot capture all the benefit of research, and so cannot make effective market-based decisions to invest alone.

There are many ways of describing research – pure research; blue skies research; curiosity driven research; applied research; directed research – but these risk meaning getting lost in a maze of definitions and semantics. Scientists at CERN have been exploring the very frontiers of knowledge, but doing so within a highly managed and structured environment – both directed research, but also in many ways the very definition of blue skies research.

However, we can say that in the broadest terms: around one third of Government's funding to the science and research base goes on block grants to universities from HEFCE and its devolved

counterparts; one third through Research Council grants to universities; and one third to Research Council institutes and international subscriptions. HEFCE and Research Council funding perform complementary functions within a single system: HEFCE and its devolved counterparts provide block grants to universities to spend as they choose, rewarding past performance; Research Councils provide grants for future research and training. Some of this funding pursues specific goals, much of it is driven entirely by the curiosity of researchers.

Quite rightly, this adds up to a substantial level of freedom for academics to pursue curiosity driven research, while also making space for the pursuit of specific challenges.

"The challenge is to reap an economic benefit from this scientific excellence and capability without clunky interventions"

Increasingly there is a recognition of the contribution scientific advances can play in delivering economic growth. Michael Porter observes that economic growth has gone from factor driven to investment driven to now being innovation driven. These scientific advances today, however abstruse, will be the basis of everyday technologies tomorrow – you need Einstein's physics to operate a modern GPS system. The challenge is to reap an economic benefit from this scientific excellence and capability without clunky interventions that risk undermining the open curiosity-driven research which is what makes us special in the first place.

One reason science in Britain is so excellent is that Ministers do not interfere in the allocation of funds for particular science programmes – the Haldane Principle. This principle covers current expenditure science which is within the ring-fenced £4.6bn annual resource budget. Governments do however have a more direct role in deciding on the allocation of major science capital spending. And there is also a role for Government in deciding broad areas of technology to support through the Technology Strategy Board before they have reached full commercialisation. Even in

these important areas of capital spending and technology support however Ministers do draw on expert advice. This Government has commissioned and published this expert advice so that the basis for our decisions on priorities is transparent. There have been three main exercises, all drawing on advice from across the research community. First, the Technology Innovation Futures report was published in 2010 and updated in the Autumn of 2012: it was overseen by the Government Office of the Chief Scientist. Secondly the TSB has also published its Emerging Technologies and Industries Strategy in 2010, which was an important technology foresight exercise. Thirdly the latest updated advice from the Research Councils on long-term investment in science infrastructure was published in November 2012. It identified the key areas which the science and research community believed most merited further capital investment.

This third report was published alongside the Chancellor's important speech to the Royal Society. He drew on the analysis in these documents to highlight eight great technologies which these analyses suggested Government should be promoting with further capital investment and technology support. There are three main criteria for being on the list. It has to an important area of scientific advance. Secondly Britain has to have a distinctive capability. Thirdly it should have reached the stage where we new technologies are emerging with identifiable commercial opportunities.

The Chancellor followed this up with an announcement of a further £600m of investment in science capital in the Autumn Statement. This, together with previous decisions to invest more in science capital, adds up to £1.5bn of extra science capital investment since the original Spending Review of Summer 2010.

The Chancellor's speech at the Royal Society invited comments and critiques of the eight technologies we had identified. By and large our analysis has not been challenged. That may reflect the large amount of consultation and discussion which went in to it

in the first place. We have done more work since then in refining them and placing them in a wider order. Now I can publish this updated account of our eight great technologies.

The eight great technologies can be summarised in the following eight propositions:

1. The data deluge will transform scientific enquiry and many industries too. The UK can be in the vanguard of the **big data** revolution and energy-efficient computing.
2. There is a surge in data coming from **satellites** which do not just transmit data but collect data by earth observation. We have opportunities to be a world leader in satellites and especially analysing the data from them.
3. There are particular challenges in collecting data from a range of sources in designing **robots and other autonomous systems**. We can already see that this is a general purpose technology with applications ranging from assisted living for disabled people through to nuclear decommissioning.
4. Modern genetics has emerged in parallel with the IT revolution and there is a direct link – genetic data comes in digital form. The future is the convergence of "dry" IT and "wet" biological sciences. One of the most ambitious examples of this is **synthetic biology** – engineering genes to heal us, feed us, and fuel us.
5. **Regenerative medicine** will open up new medical techniques for repairing and replacing damaged human tissue.
6. Although genetics is above all associated with human health, advances in **agricultural technologies** can put the UK at the forefront of the next green revolution.
7. Just as we understand the genome of a biological organism so we can think of the fundamental molecular identity of an inorganic material. Here too we can increasingly design **new advanced materials** from first principles. This will enable technological advances in sectors from aerospace to construction.

Quantum photonics is an exciting area where advanced materials and digital IT converge.

8. One of the most important applications of advanced materials is in **energy storage**. This and other technologies will enable the UK to gain from the global transition to new energy sources.

I will look at each of these in turn.

2. The Big Data Revolution and Energy-Efficient Computing

The man who invented chess is supposed to have asked the King of Persia to reward him with a grain of wheat on the first square on the chess board, compounding up on every subsequent square. At first it was fine but soon a single square had to have more grains than in the whole of the kingdom. Such is the power of compounding. Ray Kurzweil used this famous story to argue that, when it comes to data, we are on the second half of the board. We face a data deluge. The next generation of scientific discovery and innovation will be data-driven as previously unrecognised patterns are discovered by analysing massive and mixed data sets.

The power of computing and data handling is now becoming so great that classic distinctions between micro and macro effects are breaking down. We are reaching the stage of being able to model airflow across a turbine blade or the movement of a liquid through a tube at the molecular level. Computer modelling of an economy, a substance or a process is therefore becoming very different and far more sophisticated than it was even a decade ago.

Capturing value from all this data – for economic growth and social benefits such as improved health – requires a transformation in data analysis. With the right investments, the UK is well placed for the big data revolution. We have 25 of the world's 500 most powerful computers (out of 107 in Europe compared with 253 in the US, and 68 in China). But crude computing power is not the be all and end all. We have a comparative advantage in IT because of two distinctive strengths.

First, we are good at the algorithms needed to handle diverse large data sets, with strengths in mathematical and computer sciences. This goes back to our historic strengths in maths with the status it has enjoyed since Newton. Last year we marked the hundredth anniversary of the birth of Alan Turing, another great British pioneer. We have great mathematicians like Tim Gowers or Andrew Wiles (who proved Fermat's last theorem). We also have international excellence in cryptography. British scientists now play a key role in research projects which generate very large data-sets, such as the search for the Higgs boson at CERN. Our involvement in such ambitious contemporary scientific experiments has led to the UK sustaining our strengths in the software development and algorithms needed to make sense of these massive and mixed data-sets. These are capabilities which can be used across disciplines so for example a computer programme written to analyse astronomical data from millions of distant stars is now being used by neuroscientists studying brain cells.

Secondly, we have some of the world's best and most complete data-sets in healthcare, demographics, agriculture and the environment. Our long and stable history means we have reliable data sets stretching further back in time than just about any country. Their value is increasing with new ways to access and analyse them. Our own domestic meteorological records go back in parts as far as 1659, with a daily temperature record for central England from 1772, and Met Office Daily Weather Reports from 1860. We can use weather reports in captain's log books to track climate change. Indeed one of the reasons for our key role in the development of modern statistical techniques is that we had more statistics to analyse than anyone else. R A Fisher the evolutionary biologist and founder of modern statistical theory began his career at Rothamsted: some of its agricultural experiments have been running since 1843, making them the longest in the history of science. The National Health Service is highly valued by the public

and serves a large and diverse population. The wealth of data linked to unique NHS patient identifiers offers exciting opportunities for research leading to advances in patient care. The UK is well placed to do this – the NHS has a high level of patient trust and well established procedures to maintain individual confidentiality. One of the best places in the world for the study of medical risks from nuclear power stations is the University of Central Lancashire which links data from Sellafield with long-term reliable health records for the local population. From health records to transactions generated by customer loyalty cards, these datasets are treasure troves of information that can be used to create value. Britain has been conducting a nationwide Census for 210 years and its article of faith has been complete anonymity and confidentiality of the data collected from every household in the country. We perhaps needs to follow this tradition of careful data-handling, safeguarded by law, in order to reap the immense benefits of working with datasets will bring, whilst reassuring legitimate concerns about intrusion and civil liberties

"Britain has been conducting a nationwide Census for 210 years and its article of faith has been complete anonymity and confidentiality of the data collected from every household in the country"

Life sciences generally are generating unprecedented amounts of data, especially genomic sequence data and imaging data, whose exploitation requires all of the tools of e-science as well as novel computational architectures in which the storage of many petabytes of data is fully integrated with the necessary computing and data transfer capacities. The UK funds and is host to the European Bioinformatics Institute outside Cambridge, which has more than 1 million separate users every month.

A classic scientific project that the UK will now be able to support further is world's biggest radio telescope the Square Kilometre Array (SKA). Its dishes and antennas will be spread across the deserts of South Africa and Australia, as far as possible

away from mobile phones and other man-made sources of interference which would otherwise block our view of the radio Universe. The project is being managed from Jodrell Bank, the home of radio astronomy. The SKA will generate data on an extraordinary scale – its 3,000 dishes and new aperture array receivers will generate data traffic up to twenty times greater than the global traffic on the internet. That requires new breakthroughs in computing systems and data analysis and the UK will now be well placed to lead this.

These data sets are not just for the physical and medical sciences. Social science is being transformed and again Britain is the world leader because of our successive birth cohort studies going back to 1946, a unique resource for understanding social change. Despite all the financial pressures the Government has invested £23.5m in the ESRC-led Life Study, the most ambitious birth cohort study yet, which will track around 100,000 children from birth. Previous studies have tended to be shaped either by a medical perspective or by social science. This will be most ambitious in the range of data so that for example genetic data can be linked to environmental data and then information on educational outcomes. The funding will also go to improving links between that and previous cohort studies.

The Government and its agencies collect a lot of these data for administrative or other purposes. It is of course essential that confidentiality and anonymity are completely protected. Provided we do this we then have a data resource that can help us understand our society and which can be harnessed imaginatively by outside experts in ways that the conventional public sector was never going to do. That is why we are opening up anonymised administrative data sets for wider public use. We have a great opportunity to be a world leader in Open Data. The Technology Strategy Board has helped to finance the Open Data Institute, which opened in December 2012 to investigate and promote this opportunity. The ESRC-led Administrative Data Taskforce set out bold proposals

for improving access for researchers to anonymised data whilst protecting its confidentiality.

The arts and humanities also have much to gain from these new analytical techniques. It becomes possible to have an accessible record of every work of art in a British public collection. New types of literary analysis emerge. Previously unrecognised connections can be made between texts or other works of art. The BBC drama series Garrow's Law was based on recently digitised 18th century trial records from the Old Bailey. The challenge is of course that the very techniques of digitisation which unlock this potential also make artistic creations more easily reproducible than ever before; that is why this Government has at last tackled the challenge of updating copyright law drawing on the important report by Ian Hargreaves.

There are major commercial opportunities if we can make the UK one of the world's leading IT centres. We already have in ARM, one of the world's leading designers of high performance computer chips. It is a spin off from the BBC Acorn computer project. Edinburgh and Daresbury in Cheshire are two of the world's centres for high performance computing, funded by the UK Research Councils. IBM's research centre in Hursley, Hampshire is one of Europe's largest single centres for writing Linux software. The Shoreditch area of east London, 'Tech City' has a booming cluster of young web technology companies and innovators. In July 2008, it was home to some 15 high tech companies: today it hosts over 1200.

IT is thriving in these urban environments and it is worth understanding why as it gives us another insight into our comparative advantages. The sheer density of data about us living closely together in a city is of enormous value. So the challenge is to link up the data about everything from traffic conditions to energy use to enable cities to work better. Humans are middle men who can be cut out as the internet of things links them without us. Britain

was the first country in the world to go through the crucial social change of having more than half our population living in cities. We went through that barrier in the mid – 19th century. The rest of the world went through it in 2008. We can be leaders in delivering smart urban services to the world's new megacities. These services range from very software through to hardware.

Researchers at the University of Southampton's world-leading Optoelectronics Research Centre (ORC) are pioneering the innovative potential of photonics – the science and application of light. The applications are diverse. Lasers and fibre-optic networks power modern high-speed communications and the internet. Laser surgery has revolutionised healthcare and laser technology is vital to modern manufacturing.

We also have a particular opportunity in energy efficient computing. IT is an increasingly heavy user of energy. Some large scale IT facilities are shifting to Scandinavia or Ireland to save cooling costs. Energy-use is driven by the number of calculations. Poor quality software come with a high energy cost. Smart algorithms which get to a result with less effort need less energy. We may not have the world's most powerful computer but we have a number of the world's most energy efficient super computers. This means the UK is well placed to solve the challenges posed by clusters like the City of London which are close to reaching their energy and computing capacity. At the smaller scale, this means UK research leads the way in developing longer-life mobile communications such as mobile phones and tablet computers.

More and more products and services are designed, tested and delivered digitally. High-powered computer based modelling is replacing traditional physical prototyping to speed entry to market. Car-makers and aerospace manufacturers can design new cars or aero-engines more rapidly, and this same approach is now being applied to the design of offshore wind turbines in the new Offshore Renewable Energy Catapult. It is also being used in Catapults

focussed on extracting the maximum value from our cities and transport systems. And it's not just big systems that are complex. In the past you had to monitor a new shampoo or cleaning product for six months to see how it would store before launching it on the market – now you can model its behaviour at the molecular level. One scientist was modelling the processes that keep chocolate attached to biscuit to make a Hobnob. Understanding what is happening to chocolate at the molecular level is enabling us to develop chocolate that does not melt in warm climates – crucial for extending the market.

Business says we must out-compute to out-compete. But there was a real danger that we would lose our strong position in e-infrastructure. For a start we needed not a plan – the world is too fast moving and uncertain for that – but a shared understanding across the academic community, business and Government of the key trends and what each should be doing to take best advantage of them.. That is what we are now achieving and the Government is increasing its investment in high performance computing. Further investment in national high performance computing (HPC) services will provide research and industrial access to tomorrow's leading edge simulation technology. Big businesses will invest alongside us as they see Britain as a centre for these technologies. Small companies in the supply chain need to be able to access these services and learn how they can use them.

We are getting closer to a full model of the British environment. For example, real time and forecast river water quality and quantity data allied to integrated models of our rivers, could enable better treatment processes and flexible consents to discharge. That could save UK companies significant money, whilst safeguarding the environment and delivering carbon savings for the UK. The new Centre for Environmental Monitoring from Space (CEMS), will make it possible to store and manipulate high volume environmental observations and simulations. The system has already

enabled the analysis of new high resolution simulations of cyclones – work which has significant impact for the insurance industry. More multi-institutional projects are under way, including work on geo-hazards, ozone depletion, high resolution weather, and future climate. Space is an increasingly important source of new data to help us understand our world and that is one reason it is our next great technology.

3. Satellites and Commercial Applications of Space

People sometimes think of space as vainglorious conspicuous consumption not practical investment. But actually space has not just potential but practical value today. It is one of the most important and growing sources of data. Much of the data deluge is being generated by satellites, and even more data is being transmitted via satellite links. Google estimate that a third of web searches are about place and satellites are now crucial for accurate measurement of where we are and the condition places we care about are in. Satellites enable us to monitor an extraordinary range of environmental and meteorological changes affecting our planet, including: observing deforestation to enable the authorities to reduce illegal logging; measuring changes in polar ice so we can determine the impact of climate change; calculating the carbon dioxide emitted by coal fired power-stations across the world; and producing deformation maps showing the impact of earthquakes within minutes. One of our new investments in e-infrastructure, the Centre for Environmental Monitoring from Space, will enable us to do more to analyse data sets and develop products and services that will help governments, business and the general public respond to environmental change. Drawing on satellite data, and combining it with data from ground-based and airborne sensors, will bring us closer to fulfilling the dream of a national environmental monitoring system.

At the moment the Met Office has more raw data than it can analyse rapidly despite having one of the country's more powerful computers. The single most important determinant now of the accuracy of weather forecasting for the whole meteorologi-

cal research community is the capacity of IT systems to handle satellite data. We will be playing a leading role in making the next generation of meteorological satellites and investing in the e-infrastructure to use the output.

After the very successful outcome for Britain of the four-yearly ministerial meeting of the European Space Agency, ESA's Telecommunications and Integrated Applications Directorate will be moving to Harwell, outside Oxford. Like Daresbury, Harwell Oxford became an Enterprise Zone in 2012 and is rapidly becoming a cluster of space-based research and businesses. It will also be the home of the Catapult Centre for applying space-based data. We are once more seen as a leading space science nation.

Britain was third into space, after the US and USSR. Our first satellite, Ariel 1, was launched in April 1962 on an American rocket, though within months it was disabled by an American atmospheric nuclear test. We developed our own launch capability and are the only country to have given up such a capability having developed it – much of it was then absorbed within what is now the European Space Agency's Ariane programme. For a major advanced economy we have a very small public sector space programme – and indeed the UK Space Agency, bringing together our civil space programmes, was only formed in 2010.

"We developed our own launch capability and are the only country to have given up such a capability having developed it"

This unusual history has given us distinct comparative advantages – in satellites, in new launch technologies and in industry structure.

British companies have focussed on making satellite technology more affordable with smaller, lighter-weight satellites that lower the cost of commercial launches. Surrey Satellites Technologies (SSTL), one of the UK's single most successful university spin-outs, is the world leader in high-performance small satellites. Roughly 40% of the world's small satellites come from Guildford

– and now even smaller nano-satellites are coming from SSTL and Clydespace in Glasgow. Instead of a massive tractor type vehicle trundling across Cape Canaveral think of a courier with a small satchel delivering a satellite 10 x10 x 30 centimetres from Scotland to Baikonur. A powerful small camera on a satellite the size of a shoe-box can observe natural disasters for emergency relief, monitor deforestation, or observe rapid movement of small ships off the coast of Somalia. We are also developing an impressive track record with the bigger satellites too, with about a quarter of the world's commercial telecom satellites made here in the UK by Astrium.

We can also skip a generation in launch technologies as we are not trying to protect an existing conventional rocket system. At the moment space launch technologies are one-off and not reusable. A space launch costs many tens of millions of pounds and the launch vehicle is expendable – it is like flying a jumbo jet to Los Angeles and destroying it on arrival. The future is reusable technologies, going beyond the now decommissioned space shuttle, to space planes launched from runways rather than launchpads, which can be used for putting satellites into orbit, for low gravity research and construction of labs and for space tourism. British technology could be the first to break through to a truly reusable space plane, with the SABRE engine being developed by Reaction Engines at Culham in Oxfordshire. And in the shorter term, Richard Branson's Virgin Galactic will be flying commercially within a couple of years. Although initially marketed for sub-orbital space tourism, their technology will also provide a launch service for small satellites. But the absence of any European aviation regulation for these hybrid vehicles means they can be launched across the rest of the world but not in the EU. This is especially frustrating as there are opportunities for the UK to host a space-port if we get the regulatory framework correct.

Britain is currently ahead of most of the rest of the world in how we run our space programme – we have a vigorous commer-

cial sector and no big state-run space technology organisation at the centre. Instead of central contracts, we rely on cooperation to ensure that British science has the technological foundations for the future and that British companies continue to win contracts from across Europe and around the world. Instead of a big central pot of funding, the space sector is a case study in how a modern industrial strategy can be developed through real collaboration and strategic, targeted investment.

We already have strong and growing space businesses. Indeed we have a much more favourable balance of commercial and public sector space activity than any other advanced nation. London is proving to be a major draw for growing space businesses. Already the Silicon Roundabout is anchored by Inmarsat, a FTSE 250 company built on space technology, and surrounded by growing space companies like Avanti and Paradigm. One reason is that our financial services industry has world leading skills in financing and insuring space business – it is important that misconceived international regulation does not jeopardise that.

There is an assumption that broadband has to be delivered by fibre optic cable (another British invention), but one way in which we are using space technology to solve 21st century problems is in the delivery of telecommunications. Satellites too have a role in delivering broadband, particularly in hard to reach places where our assumptions about fibre-optic networks do not apply. There need be no not-spots anywhere in Britain as we are fortunate to have already satellites targeted on delivering broadband services to the UK. They may not get to full super fast broadband speeds but it is possible to carry out all the basic web based functions from email to Skype. An independent report to the Space Leadership Council confirmed that reports of the technical problems in such a service are exaggerated. This is a business where Britain is a world leader. There are crucial emerging economies which will struggle to build up the fibre optic infrastructure necessary for a 'wired'

future. Instead they could be using satellite services, and British businesses, like Avanti, can play a major role in providing these services. We are already the world leader in providing telecommunications services across the oceans with Inmarsat. It would be a logical extension of this crucial role for web-based services to reach the International Space Station, which Britain has just joined as a member in our own right. An international consortium is looking at putting the space station on the web. It would be fitting if Tim Peake, the British astronaut in the European Space Agency were to use a flight to the ISS to connect it to the Web via British-built technologies.

Manned space flight captures the imagination and is one of the most powerful ways of getting young people studying science. In the US they still talk of the Apollo effect when young people surged into the sciences. But a lot of space exploration can and will be done by robots and autonomous vehicle. That brings us to our third technology.

4. Robotics and Autonomous Systems

Robots acting independently of human control – which can learn, adapt and take decisions – will revolutionise our economy and society over the next 20 years. Our wider manufacturing industry has so far been a slow adopter of industrial robotics – (the UK has 25 robots per 10,000 employees in non-automotive sectors; whilst Japan and Germany lead the world with 235 and 127 robots per 10,000 employees respectively.) This slow adoption of a crucial new technology may be one reason for the continuing lags in British industrial productivity and is one of the issues our work on advanced manufacturing is addressing. It is also a key strand of the Technology Strategy Board's support for advanced manufacturing. There is a small budget to encourage SMEs to shift to robotic manufacturing techniques. We aim also to make it easier for them to try out these techniques at demonstration facilities. But our researchers have some distinctive leads in other areas which we must exploit.

In Japan the focus is on humanoid robots to deliver services to elderly people in the world's oldest society – where sales of nappies for babies are now exceeded by nappies for old people. In Germany the focus is on advanced manufacturing techniques. The most dramatic advances in motor cars and aerospace are in the US where these technologies are about to enter the mainstream. Last year Congress passed legislation requiring the Federal Aviation Authority to develop and implement operational and certification requirements for public unmanned aircraft systems by the end of 2015. The FAA estimates that roughly 10,000 active civilian unmanned aircraft systems will commence operations once the regulations are in place.

They say the plane of the future will be flown by a man and a dog – the man's job is to feed the dog and the dog's job is to bite the man if he touches the controls.

There is a similar time frame for the development of unmanned automobiles. Here the crucial breakthrough has come from California which also passed legislation last year for implementation by 2015 providing a legal framework for driverless cars. They are likely however still to require a driver in the driving seat in case manual over-ride is necessary. This will inhibit the full benefits of for example sending one's car off to a suitable parking place or to pick someone else up after dropping you off. In the US as well as Government setting a regulatory environment DARPA has been promoting these technologies through sponsoring grand challenges and funding them.

We are not leaving the development of these technologies to others. With the strength of our automotive and aerospace industries it would be irresponsible if we did not support research in this area. The Technology Strategy Board has invested over £50m into Autonomous Systems Technology Related Airborne Evaluation & Assessment (ASTRAEA) programme over the last five years. A collaboration between the EPSRC and BAE Systems has successfully demonstrated flapless flight by an unmanned vehicle. The entire body of the craft is shaped like a wing and air jets across the wing control direction of travel instead of conventional flaps: this means lighter and fewer moving parts, lower maintenance and less noise.

"We are not leaving the development of these technologies to others"

We have some distinctive strengths, going back yet again to our abilities in software programming and data handling. Effective handling of data from a range of sources is key to autonomous systems and we have real skills here. Indeed these strengths mean that we have taken a rather different route from the US. There the dominant player in automotive software systems is Google and

they use GPS and Google maps alongside other information. One of the world's first fully autonomous cars, not dependent on GPS and Google maps, has been developed by the Oxford Mobile Robotics Group with close involvement of the car industry. There is even a facility in Nuneaton where these new vehicles can be developed and tested. Leading Japanese car companies, notably Nissan, are currently backing R&D on these technologies in the Oxford/Warwick/Birmingham automotive cluster as well as in California. There are likely to be incremental steps to a fully autonomous vehicle as gradually people get back time spans of 15 or 30 minutes when they would previously have been manually in control of driving a car at steady speeds along a motorway, or at slow speeds in traffic jams.

It was an extraordinary feat of engineering to land NASA's Curiosity probe on Mars last year. Its Mars Rover vehicle is however largely controlled from Earth with a delay of at least seven minutes as instructions travel to Mars. The European Mars Rover vehicle, due to land in 2018, is more autonomous, using mainly British technology to enable it to travel further during the Martian day and therefore carry out more investigations during its design life. In the UK we have a comparative advantage in these fully autonomous systems.

Our comparative advantage comes from our skill in algorithms to programme autonomous systems to handle massive data flows fast. The unusual breadth of our world-class research base combining software, engineering, clinical medicine and ethics gives us a lead in the development of this truly cross-disciplinary technology. (Through the strength of the Humanities in our universities we also have a strong position in the ethical issues that arise – programming a scavenging robot and defining how it acts and in what circumstances should not be done in an ethical vacuum.) The Technology and Innovation Futures report identifies service robotics as an area of high growth potential for the UK in the 2020s. We will ensure that we retain our research capabilities and the

allocation of extra funding for robotics research within the extra allocated in the Autumn Statement will make this possible.

The UK can lead in developing these technologies for sectors as diverse as defence, healthcare, manufacturing, agriculture, transport, entertainment and education. In Edinburgh robots play (rather slow-moving) football in real time. In the Bristol Robotics Laboratory they are developing self-powering robots which collect dead flies and other detritus and place it in a back pack container of bacteria which converts this into electric power. Industrial partners for these developments include BAE Systems, DSTL, Schlumberger, Ford, Rolls Royce and Airbus. The University of Hertfordshire are making breakthroughs in helping profoundly autistic children who find it easier to interact with a humanoid robot than a human. The autonomous device to clean swimming pools is a forerunner of the autonomous vacuum cleaner which is close to entering the mass consumer market with Dyson a key player. We are strong at research in robotic mining, linked to Rio Tinto Group, which could replace much human mining over the next 20 years or so. We also have a strong lead in autonomous underwater vehicles, developed over several decades. The National Environment Research Council (NERC) has led the world in use of autonomous technologies in the exploration of our oceans – which poses challenges as demanding as the exploration of space in many ways. The Autosub series of vehicles developed by NERC's National Oceanography Centre (NOC), have achieved a number of firsts including exploration underneath rapidly melting ice-shelves in both the Arctic and Antarctica, as well more recently discovery of the world's deepest and hottest hydrothermal vent in the Cayman Trench. The latest generation of Autosub, designed to remain at sea for up to 6-months and with a range of 6,000 km, will be deployed on its first science mission in 2013, and ultimately holds the promise of opening inaccessible regions of the deep sea and polar oceans, enabling for the first time major unmanned missions to Planet

Ocean such as fully autonomous transits of the Arctic Basin in order to monitor this rapidly changing environment.

Marine robotic systems will also be critical to cost effective routine mapping and monitoring of the oceans and seas, addressing the gross under sampling of the oceans – we know more about the surface of Mars and the Moon than about the sea floor – including the UK's own waters. This information is needed to support sustainable use of marine resources, monitor the impacts of human activity, especially as our activity moves into deeper water and more extreme environments, and to develop reliable seasonal weather forecasts, which are dependent on understanding ocean variability. Through NOC and universities such as Heriot Watt, the oil and gas industry have increasingly adopted autonomous vehicles, while defence is also benefitting from advances in underwater autonomy, with NOC supporting both DSTL and the Royal Navy in using autonomous vehicles to understand and exploit the battlespace. Indeed an NOC glider was the first to ever be operated from a Royal Navy ship during 2011, in the Indian Ocean.

The market for medical robotics is growing around 50% annually worldwide. The UK has a strong track record in pioneering medical and surgical robotics. They can enable operations to be done remotely. They can replace hands and arms. Exo-skeletons give movement for severely disabled people with controls linked directly to the brain. iLIMB an upper limb prosthetic has been developed by Touch Bionics, a Scottish SME, in collaboration with the University of Edinburgh. It is the world's most dexterous multi-fingered anthropomorphic robotic prosthetic hand and has now been fitted on several amputees. They have now filed patents for improved sensory feedback for grip-force. The NHS initiative in assisted living – three million lives – is an opportunity to promote this and similar technologies to more patients who could benefit from it.

As well as American legislation speeding up the spread of robotics technologies there has been one other development which has

given similar impetus to this technology – the Fukushima disaster. The clean-up is taking place in very difficult conditions with rubble and debris that would make it hard to work anyway without the additional hazard of nuclear contamination which in turn requires workers to wear cumbersome suits that impede effective working. All this points to the need for robotic systems: Fukushima is likely to lead to a step change in these technologies. OC Robotics led by Rob Buckingham, who is also a visiting professor at Bristol Robotics Lab, is pioneering autonomous snake arm robots for use in confined and hazardous spaces. Advanced algorithms control their motion. The global nuclear decommissioning market is estimated to grow to over £1trillion and we are strengthening links between British business and our own Nuclear Decommissioning Authority to ensure we take full advantage of this very significant opportunity. The Technology Strategy Board will be pursuing these opportunities in Japan and elsewhere.

Perhaps the most futuristic application of these technologies is insect-size surveillance vehicles being developed at Oxford. They use flapping wings and micro cameras so as to mimic real life insects. As well as defence application they can also help with monitoring natural disasters: but probably their widespread application may be twenty years off. It is one example of the increasing interest in improving design and engineering techniques which mimic natural processes. Meanwhile some of the things we are discovering about the natural world are bringing it closer to dry IT technologies.

5. Where Dry Meets Wet – Life Sciences, Genomics and Synthetic Biology

So far we have focussed on the data revolution and two general purpose technologies which are developing alongside it. Researchers tell me the future is linking "dry" computer sciences and "wet" biological sciences. While the world was preparing to move from analogue to digital technologies, we were also discovering that the key to the genetic code, DNA, is, rather helpfully, itself digital. Many of the critical discoveries related to DNA were made in Britain, in perhaps the greatest post-War research institute – the Laboratory of Molecular Biology in Cambridge. It is not just the original discovery of the structure of DNA by Watson and Crick, drawing on work by Rosalind Franklin and Maurice Wilkins. It is also the development of genetic sequencing by Fred Sanger and others. Indeed the world's key DNA sequencing technologies all come from UK research labs, while the Sanger Centre at Cambridge, under the leadership of the Nobel-prize winning John Sulston, provided a major contribution to the sequencing of the human genome. And of course the NHS with its nationwide patient records is another great national asset. The pharmaceutical industry is responsible for **almost 30%** of all business R&D in the UK. Put all this together and life sciences has to be a key part of our future science and technology strategy.

The challenge is to maintain this lead. The Prime Minister launched our life sciences strategy in December 2011 to do just that.

A year later he made an important commitment to sequence the genetic code of 100,000 NHS patients as a crucial tool of genetic research. What we used to think of as a single condition – prostate cancer for example – is increasingly turning out to be one name for several difference genetic mutations. A drug which works very effectively against one may have no effect on another. So Herceptin for example works with some breast cancers but not others. This knowledge means that the future lies in what is called stratified medicine which is far more accurately targeted on specific conditions. The Research Councils and the Technology Strategy Board have been working with CRUK, ARUK and NIHCE on a £50m programme to develop the integrated suite of diagnostics and therapies to address this growing market.

These basic insights from the life sciences inform both synthetic biology and regenerative medicine. The significance of these ideas also extends beyond human medicine to agri-science and even further. Thus, British laboratories have contributed substantially to the sequencing of many other genomes such as those of barley, wheat, tomatoes and pigs. So the next three areas of technological advance are linked.

"The significance of these ideas also extends beyond human medicine to agri-science and even further"

Synthetic biology is the redesign and engineering of biological systems and processes for new uses. It takes naturally occurring genes and engineers new genes and hence organisms from them. These organisms can be designed to meet a particular need. They say that synthetic biology will heal us, feed us and fuel us. It was identified in the TSB's "Emerging Technologies and Industries" Strategy in 2010 as one of our key potential high-growth emerging technologies. We are now one of the leaders in applying engineering techniques to genetics. The aim is to standardise engineering–style processes for the creation of new genes.

It is this profound change in the way in which biological processes are shaped that makes synthetic biology so significant.

There are three major global players in synthetic biology – the US, China, and the UK. Learned societies from these three countries are trying to agree world standards which will shape the future industry. The Stanford-based Bio-bricks Foundation is leading the creation of a library of standard biological parts. Imperial College London is one of the worlds leading UK centres using classic computer aided design for genetic engineering. This is a good example of how we can leverage our scientific strengths to give us a role in standard setting. One of the reasons Vodafone is a global telecoms company is because at the right moment we got European standards based on the technologies they were using.

One spin-off company using techniques developed at Imperial is a good example of the potential of this technology. Green Biologics based in Abingdon, Oxfordshire, is using synthetic biology to develop microorganisms which convert woody biomass such as crop residues into butanol for use in road fuels and as an alternative source of chemicals for industry from fossil-fuels. We are also pioneering the use of biological organisms to convert carbon monoxide into fuel. Another project is using microorganisms in the production of biomethane. Fermentation lies behind these processes but using synthetically engineered organisms to ensure that the fermentation process is effective. The original research into the organisms is by no mean the end of the story. The next stage is just as tricky– the steps between an organism in a lab and a full-scale industrial process. It involves funding prototypes to show the fermentation can work on a larger scale than the lab. This is where the TSB and catapult centres can help with demonstrator projects which can encourage industry to invest.

The more we can invest at the early stage to reduce the uncertainty and risk of these technologies and to show it can be scaled

up, the more business will invest too. This involves the Research Councils and the Technology Strategy Board working together with research groups and industry. The UK Synthetic Biology roadmap highlights where we need to address gaps and improve access to cutting edge infrastructure.

6. Regenerative Medicine

Regenerative medicine involves restoring function by replacing or restoring human cells, tissues or organs. There are three main approaches – transplantation of cells, tissues and organs, stimulation of the body's own self-repair mechanisms; and the development of biomaterials for structural repairs. It could mean for example the growth of new cells for new nerve connections for paralysed patients or new heart muscle for patients with a heart condition. A crucial challenge is the generation outside the body of a renewable source of transplantable tissue. The Nobel Prize in medicine was jointly awarded to John Gurdon of Cambridge and Shinya Yamanaka from Japan for their revolutionary work revealing that mature, specialised cells can be reprogrammed to become immature cells capable of developing into all tissues of the body. Martin Evans of Cardiff University won the Nobel Prize in 2007 for pioneering the growth of embryonic stem cells in mice. Their findings have revolutionised our understanding of how cells and organisms develop and led to the concept of cloning being applied to animals not just plants. Ethical concerns, particularly over the use of stem cells has attracted considerable attention, sometimes obscuring the real medical advances which are now being achieved, with British scientists in the lead.

The Government's report in 2011 'Taking Stock of Regenerative Medicine in the UK' confirmed that we have a leading position in the science and commercial translation of regenerative medicine. This comes from our cross-disciplinary research base. It is also because we have a well-balanced legislative and regulatory framework. This is a contrast to for example the uncertainties about the American regulatory regime after President Bush banned the use of

federal funds for embryonic stem cell therapy research and which President Obama has only recently been able to resolve.

We have world class research in centres such as Edinburgh (where Dolly the sheep was cloned), Cambridge, Leeds, and London. The Medical Research Council is funding centres for clinical grade stem cell lines at Manchester, Sheffield and King's College, London. It also supports the UK Stem Cell Bank which was the first facility in the world established to store and distribute such stem cell lines. In cardiovascular research centres, such as at the Hammersmith campus in West London, we can now grow for example heart muscle tissue in the lab which you can see spontaneously starting to beat when it reaches critical mass. We can grow new tissue and then remove distinctive features that cause rejection by the host, opening the door to a time where patients will be able to avoid having to spend the rest of their life time on drugs to combat tissue rejection.

There are a range of medical conditions which are now becoming treatable as a result of these advances. A team at UCL's Institute of Ophthalmology is working with Pfizer on age related macular degeneration, the leading cause of sight loss. They are growing replacement retinal pigment cells in the lab and then surgically implanting them in the back of the eye. Parkinson's disease is caused by the degeneration of dopamine generating cells in the brain. Researchers in Cardiff have shown it is possible to grow new dopamine generating cells and are developing strategies to transplant them into the brain. And very recently a team at Cambridge took stem cells from the noses of dogs, transplanted them into the spinal cords of dogs with serious spinal cord injuries, and made it possible for them to move hind legs that had previously been paralysed.

Our international competitors are investing heavily in translational research. We need to match them in moving from the research lab into patient care.

We are also trying to use our scientific lead to help shape the regulations for this emerging technology. In the past year the British Standards Institution has published a set of three cell therapy and regenerative medicine standards.

The global regenerative medicine industry was valued at $1b in 2011 growing to $5b by 2014. Given our leading position in the field we are well placed to take advantage of the rapid growth in this market provided we can move to patient care and commercialisation promptly and effectively. That is why we have established a £50m Cell Therapy Catapult Centre at Guy's Hospital in London.

The challenge is to get more investment from life science companies alongside medical research funded by Government and charities like the Wellcome Trust and the British Heart Foundation. Securing a patent is often a crucial step in enabling smaller start up companies to get new commercial investment. The European Court of Justice ruled in the Brustle case that inventions that involved stem cells derived from human embryos cannot be patented. The European Commission have agreed to monitor the impact of this ruling.

To build further on the excellence of our science base, and add to the momentum established through recent investments in the translational agenda, we will need to develop high-throughput and automated technologies for safety assessment of cells, for preclinical work, and for manufacture of clinical regenerative medicine products. In the US public agencies like the National Institutes for Health are funding work on these manufacturing issues and we intend to do the same. In addition stem cell science is transforming our approach to disease modelling and drug development. The same technologies will also be key for supporting the scale-up and assay development needed to provide cell-based drug screening and toxicology for the pharmaceutical industry. Further investment in this area will therefore be essential in ensuring that the UK can retain its currently world-leading position in biomedical research and development.

7. Agri-Science

Agri-science is not strictly a general purpose technology like the others. Nevertheless it is right to include it because developments in life sciences are often taken to focus on human medicine whereas the transformation of our understanding of genetics and the wider biological sciences is having an enormous impact on agriculture and horticulture as well.

These developments are happening at a time when they are desperately needed. The UN forecasts that global food production will need to increase by over 40% by 2030, and 70% by 2050. Yet water is becoming scarcer, there is increasing competition for land, and climate change is putting added pressure on production. Sir John Beddington, the chief scientist has rightly made the challenge to domestic and global food supply over the next thirty years one of his personal priorities. Our aim is sustainable intensification of agriculture – raising the productivity of agriculture, while protecting the environment, and diversity, and contributing to the mitigation of climate change.

Britain did not just lead the Industrial Revolution, we pioneered the Agricultural Revolution too. From leading that Agricultural Revolution in the late eighteenth century to new biotechnology-led advances, the UK has remained at the forefront of agricultural research. Our historic collections of data and samples are a crucial research asset. The Broadbalk winter wheat experiment began at Rothamsted in 1843. It is the world's longest-running agricultural experiment and represents a unique resource, charting the long-term effects of agricultural practices and a changing environment on crops, soils and farmland ecosystems. The John Innes Centre in Norwich led the introduction of dwarf crop varieties, a

crucial element in the Green Revolution of the 1970s and remains a world-leading centre for plant science. The Pirbright Institute in Surrey, (formerly the Institute for Animal Health), is crucial not just to understanding animal diseases but also to combating the increasing threat of zoonotic pandemics in humans, caused by viruses crossing the species barrier from for example chickens or pigs to humans. The Roslin Institute in Edinburgh was the home of Dolly the sheep, and is a world leader in animal and poultry genetics. With this world class agri-science we can develop better seeds and more productive farm animals.

In the past twenty years however we have become complacent and taken for granted easy access to cheap food. The pressures families now face with rising food costs is a reminder of the need to innovate in food production to hold costs down. The decline of the growth of agricultural productivity in the USA has been linked to declines in funding for agricultural research. The adoption of new technologies is crucial for improving agricultural productivity and feeding the world at a price we can afford.

“The adoption of new technologies is crucial for improving agricultural productivity and feeding the world at a price we can afford”

One of our challenges in the UK is that we have not been as effective as we should be in spreading the advances from our agricultural research institutes out to the working farmer. We also need capital investment in domestic agriculture to exploit and maintain this capability.

One barrier to progress is the belief that good food has no connection with scientific advance. The industry faces a shortage of food scientists yet its own advertising sometimes advertises its own products with happy peasants picking delicacies in a rural idyll. Agriculture is a key high-tech industry of the future. The modern tomato is at least as sophisticated a scientific achievement as an Apple (iPhone). The modern tomato is the result of sustained scientific effort in genetic breeding and technologies which have

gone into modern enclosed horticulture. Last year alone several thousand scientific articles with relevance to tomato genetics were published. Within the UK the tomato industry is worth £625m annually.

Food production is actually our biggest single manufacturing sector, responsible for 7% of national output. We can already see some of the trends shaping agriculture in the future. Here are four examples of future technological advances which we are backing with research funding.

The future could be the kind of horticulture one can see in a research facility like the Stockbridge Technology Centre in Yorkshire. They have a warehouse with vertically banked rows of raspberries, broccoli and many other green groceries. They are growing indoors under LED lighting provided by Philips Lighting. LEDs are not hot, unlike conventional light bulbs, so you can bring them down closer to the crop and then expand upwards in many layers. Researchers from the University of Lancaster are researching the specific wavelengths from the photosynthetically active spectrum to get the right "light recipe" for each crop. This project, LED4CROPS could be the future of urban farming – with an extension out the back of the local supermarket where greens are grown. This is the type of innovation that should be encouraged.

Wheat provides a fifth of all human calorie consumption but improvements in wheat yields have been slowing down and climate change threatens future yields – for example, drought, heat stress and flooding are increasing problems. UK researchers led the decoding of the wheat genome. It is a research priority to harness our world lead in wheat research to improve wheat yields, using more sustainable practices that reduce chemical and energy inputs, maintain and improve soils, and reduce emissions and run-off pollution.. This raises UK wheat production, generates exports as new wheat strains are exported, and contributes to international development as for example we create new strains of

drought-resistant wheat. We now get on average about 9 tonnes of wheat per hectare from a British farm (about 1 tonne in the wet summer of 2012 from organic farms that do not use fungicide). Rothamsted's 20:20 wheat programme, launched last year, aims to deliver wheat yields of 20 tonnes per hectare in 20 years. Such a doubling of wheat yield in the UK would generate £1.5bn at the farm gate. Building on UK excellence, BBSRC is taking a leading role to promote collaboration in wheat research through the formation of a Wheat Yield Network involving 20 funders from 16 countries.

Chickens are the world's biggest source of meat, and are particularly important in Asia. We breed the world's chickens – of the £85bn global poultry market, 80% of breeding chickens come from genetic stock developed in the UK. Thanks to our genetics research you get twice as much chicken for a given amount of chicken feed as 20 years ago. Each year we launch a new brand of chicken which will produce many generations over a year or more before a new improved version comes along. This is possible because of close links between the Roslin Institute, with its world leading R&D, and our commercial sector.

Perhaps the biggest future health threat is diseases crossing the species barrier from animals to man. Avian flu and swine flu are classic examples. We are the world leader in studying and forecasting animal-borne pandemics. The Roslin Institute has used GM techniques to develop the world's first flu-resistant chicken. There is also a massive opportunity in developing new vaccines. It takes a long time to develop a vaccine and from TB in badgers to Foot and Mouth there is uncertainty about the value of vaccination strategies. At Pirbright, they are developing new technologies to speed the creation of new and improved vaccines for livestock so they can be available for prompt intervention at the start of an outbreak.

Agriculture can also benefit from advances in general purpose technologies. Precision agriculture is a classic example. As satel-

lites provide ever more accurate images it will be possible to see how well a crop is growing across different parts of the same field and then use GPS and Galileo to locate the tractor (which could well be autonomous) precisely and control the amount of fertiliser distributed so that none is used unnecessarily. By setting a precise route for the agricultural vehicles these systems can also reduce soil compaction which can be a significant problem with the increasing weight of modern agricultural machinery and its more frequent use.

The development of agri-science across Europe is dogged by controversy about genetically modified crops. The rest of the world has rapidly adopted genetically modified crops over the last 10–15 years. Europe is finding it increasingly difficult to avoid this technology as it is widespread in animal feed and elsewhere. The EU regime is very restrictive but the Government supports research in this area and believes that, provided they pass tight regulatory requirements, GM crops should be planted commercially. Nevertheless even without GM we can harness modern IT to classic advanced genetics to accelerate conventional plant breeding techniques. The National Plant Phenomics Centre at Aberystwyth University uses automation and state-of-the art imaging technologies to monitor electronically (and non-destructively) day and night the growth of tens of thousands of individual plants in containers. The monitoring equipment can measure exactly how much what amount of feed and moisture the plants use and how their physiology responds under different conditions. This is far more sophisticated than just recording the one which ends up growing best by the end. Advanced agri-technologies such as this will enable our scientists to identify the best genetic crosses, develop improved breeds of crops that are adapted to the future climate combine the genes of different blades of wheat to get the far more growth and help achieve the 20:20 objective for wheat.

We need to do more to link our research strengths with practical application to farming practices and the food industry. That is why

a pioneering research farm platform to test practical implementation of these technologies has been established at North Wyke in Devon.

We have now considered three "dry" sciences and three "wet" ones. But we have also seen how these different disciplines are inter-connected. These inter-connections are just as strong with our last two key technologies.

8. Advanced Materials and Nano-Technology

We have just shown how LED lighting can be used to transform horticulture. At the heart of LED technology is gallium nitride, probably the most important semiconductor material since silicon. The EPSRC is funding research at Cambridge, Manchester, Bath and Strathclyde to understand better how this advanced material works.

"Widespread adoption of LED lighting would reduce electricity consumption by 10–15%"

The team led by Professor Sir Colin Humphreys at Cambridge has developed a new cost-effective way of growing gallium nitride on silicon, which in turn increases the cost effectiveness and energy efficiency of LED lighting. Since lighting accounts today for 20% of all electricity generated in the UK, widespread adoption of LED lighting would reduce electricity consumption by 10–15%. And moreover, these are being manufactured in the UK (using the technology) by Plessey. Plessey acquired this technology in 2012 and plan to produce 500 million LEDs a year in Plymouth – the first manufacture of LEDs in the UK. This is a classic example of the links between apparently different technologies and the impact they can have: it is why the sheer breadth of our scientific research is a crucial asset.

Advanced materials are a classic general purpose technology because of the range of their potential uses. The UK has a long-established reputation for excellent materials science, as well as industrial strengths in advanced materials. Wedgwood, Pilkington and the super-alloys and carbon fibre in Rolls Royce engines are all examples of successful business applications of materials research.

When the N8 Group of leading research-intensive northern universities consulted businesses in their region on research issues that they would find most helpful to their business the message came back that priority should go to advanced materials.

One example of advanced materials, meta-materials, are materials which are built from the atom up and designed to have characteristics not found in nature. There is a kind of analogy with the use of genetics in synthetic biology. Now we can try to understand the "genome" of a material at the atomic level and then create new materials with specific properties. For example, Professor John Pendry at Imperial is developing the world's first invisibility cloak which has the ability to bend light around objects behind it.

The UK has key strengths in high-performance metals, biomaterials, materials for renewable and nuclear energy, plastic electronics and composites. There is good evidence for this from the International Review of Materials, from key business partners, and the Institute of Materials, Mining and Metals. Advanced materials are a key requirement for advanced manufacturing. But we need further R&D to support the sophisticated imaging and microscopy, metrology and materials processing, fabrication and characterisation equipment that is required for both the development and manufacturing of advanced materials.

Advanced materials are a key tool for advanced manufacturing. UK businesses that produce and process materials have a turnover of around £170bn pa, represent 15% of the country's GDP and have exports valued at £50bn. There has been quite rightly a flurry of interest in 3D printing, or Additive Layer Manufacturing. This new technology is possible not just because of advances in IT but also because of advances in the materials that go into the process. It is no longer just a matter of printing out designer dolls: Southampton University has used advanced materials to show how we could print out a new aeroplane.

Materials innovation is crucial for many business sectors such as aerospace and the automotive sector. Formula One racing teams in the UK, especially McLaren which is one of our most research intensive companies, push rapid innovation in advanced materials. The future of construction is to incorporate more functions into structural materials rather than adding them as extras. Clothing is increasingly likely to incorporate advanced materials with smart functions such as health monitoring – Real Madrid have a sports shirt with textile ECG sensors which continuously monitor the heart-beat of each player – though its use is not permitted in competitive matches so it is restricted to training sessions.

Graphene research at Manchester and elsewhere has opened up other opportunities for us after George Osborne's decision to invest in it. Samsung is currently the leading business exploiting the technology but the British SME Thomas Swan – an extraordinary British Mittelstand firm based in Consett – are also interested in possible applications.

Advanced materials are also key to innovation in the energy sector – which we will look at in the next section. New porous solids are being engineered to absorb greenhouse gases such as carbon dioxide and sulphur dioxide. Nottingham University has developed NOTT-300 which absorbs flue gases into a Velcro-type strip that can then be peeled off from a chimney-lining. Scientists at Imperial College London developed a cement which absorbs CO2 as it sets: their company Novacem went into liquidation in Autumn 2012 as it could not get further financial backing. The IP was then bought by Calix, an Australian company specialising in carbon capture and storage technologies. They will continue working with Imperial and doing research in the UK but more of the gains from this technology are likely to accrue to Australian investors.

Advanced materials enable the production of both onshore and offshore wind turbines, tidal turbines and machines that capture

the energy of waves. These enormous structures have to cope with extreme environments and go on working – so both the initial properties and their resistance to fatigue have to be just right.

New advanced materials are needed for next generation nuclear fission and for nuclear fusion as well. These are being developed at Culham in Oxfordshire to enable ultra-hot plasma to be held in stable conditions. After Fukushima the market is looking for a nuclear fuel rod that does not heat so much: we may be able to develop this, using high performance computing to model the new materials we need. New forms of steel, novel welding techniques and vitrification of nuclear waste all depend on continuing to develop our expertise in advanced materials.

9. Energy and its Storage

Rather like agri-science, energy covers a range of different technologies. But we need to include them in our list. For a start the energy sector is a classic example of the need for rigorous systems analysis in for example re-engineering the Grid as new power inputs emerge and smart meters potentially affect patterns of use. America's grid is notoriously frail. We are a well recognised global leader. Again our strengths in maths and computing are crucial here.

Our university sector is developing world-class centres of excellence in nuclear energy R&D based on investment by the Research Councils and the Technology Strategy Board. And wider scientific capabilities can assist with energy technologies. So for example the Science and Technology Facilities Council runs the ISIS neutron facility at Harwell. It is a synchrotron which accelerates protons and fires them at targets to generate neutron beams, which can then be used to reveal the atomic structure of samples. EDF Energy used it to research the performance of materials in nuclear power stations, enabling them to extend the working life of two nuclear power stations by five years – a very significant gain of extra electricity.

Small Modular Nuclear Reactors have the potential to make a significant impact on the nature of global demand for nuclear energy in the decades to come. A much smaller footprint for nuclear power stations could change the public debate about acceptability and a modular design could dramatically reduce the level of investment required for new build (to perhaps only a fifth of the financing required for each of the current batch of new nuclear power stations in the UK). With our long history of working with small modular reactors for submarine propulsion and our recent public investment in state-of-the-art nuclear manufacturing

research facilities, we have an opportunity to make our mark on this global market. Rolls-Royce have already made the transition from military to civil nuclear power and see small modular reactors as a technology and a market of the future.

We also need better ways to store electricity. This need arises at three distinct levels.

First, there are the batteries in all our personal electronic devices. These use lithium ion batteries working on a chemical reaction developed at Oxford in the early 1980s. The Li-ion battery, now in almost every portable computer, tablet and mobile phone in the world, was invented in the UK in 1980 but was only made commercially viable by use of Japanese manufacturing expertise, by which time benefit to the UK was lost. It was Japanese battery companies which went on to dominate the global supply, in part built on the momentum gained from this UK invention.

Thirty years on the basic technology has not advanced much. Lithium ion batteries are not ideal for a wide range of uses. For example, there is a strong driver to reduce the thickness of Li-ion batteries for tablets and e-readers – but the manufacturing technology for Li-ion batteries has reached its lower thickness. In consumer electronics the quest is for smaller batteries with longer charge lives, which ultimately comes down to one thing – ever higher density batteries. In many cases, emerging energy storage technologies will be based on advances in nanoscience and nanomaterials, but their applicability will depend solely on their cost-effectiveness. UK researchers are leading the way in alternative energy storage technologies. The ISIS facility, for example is being used to research novel battery systems such as lithium-air, sodium and fluoride-based batteries, which provide an alternative to traditional lithium-ion technologies. These new approaches will deliver improvements in battery capacity, safety and cost, all of which are pivotal in new applications in both personal electronic devices and many other applications. For example, sodium whilst heavier

is significantly cheaper than lithium – so sodium-based batteries may be more economically viable than lithium-based batteries for energy storage needs where being lightweight is not essential.

The second level is the development of better energy storage for vehicles. We use petrol and gas because they are very effective energy storing substances left us by nature. We cannot yet match their performance but we will. One reason Nissan decided to produce their new all electric LEAF car in Sunderland was the continuing support for research on innovative batteries for cars. Investment in a new fuel cell research facility for automotive applications will enable us to align academic research with industry needs. This will be facilitated by recent investments in energy storage research. Johnson Matthey is one of the world's largest suppliers of fuel cell technology. Jaguar Land Rover are working with Warwick Manufacturing Group to develop new types of battery production – this university business collaboration incidentally being one of the beneficiaries of the RPIF scheme, receiving grant of £15m to unlock a total investment of £92m in a new R&D facility on the Warwick university campus. ACAL Energy, an SME based near Runcorn is working with STFC's Hartree Centre to develop new fuel cell electrolyte technology that doesn't require precious (i.e. rare and expensive) metals in its formulation. Intelligent Energy, a spin-off from Loughborough is developing a completely new light weight fuel cell technology, in partnership with Suzuki, which is light enough to be suitable for motor bikes. Intelligent Energy, ITM Power, Ceres and many other companies have been developing commercial products based on these ideas under an ongoing five year programme run by the Technology Strategy Board that has already invested £30m in the area.

Thirdly, there is the challenge of storing more electricity for the Grid. This is particularly important as national electricity networks become more dependent on intermittent supplies of wind power. (On 14 September 2012, a record of 10.8% of the total amount of

electricity going into the national grid came from wind.) Electricity demand peaks at around 60 GW, whilst we have a grid capacity of around 80 GW – but storage capacity of around just 3 GW. (Over a year we use around 360,000 GWh of electricity.) Greater capability to store electricity is crucial for these alternative power sources to be viable. It promises savings on UK energy spend of up to £10bn a year by 2050 as extra capacity for peak load is less necessary. Such technology would also allow large energy consumers to buy at off-peak rates, store the energy and then use it at times of their choice. This could significantly reduce (e.g. halve) energy bills for such consumers

The increased use of intermittent energy generation sources on the grid to meet binding emission reduction targets, electrification of transport, and consumer demands for efficient personal electronic equipment present myriad growth opportunities for new energy storage technologies. The UK has an internationally leading research base in energy storage basic science, but has ceded huge revenue generating opportunities in the manufacture of energy storage technologies to overseas competitors.

“The UK has an internationally leading research base in energy storage basic science”

If similar opportunities are not be lost again as energy storage technology markets diversify and expand, it is essential that manufacturing technology for energy storage devices is advanced hand in hand with basic science. While Li-ion has come to dominate portable electronics and seeks to establish a firm presence in electric vehicles, there has been a resurgence of interest in alternatives such as Na-ion, Li-S, Li-air, flow batteries, fuel cells, supercapacitors, etc – each for a different market sector and requiring appropriate manufacturing technology if commercialisation is to be achieved; indeed in many cases, manufacturing technology is the critical technology for mass market penetration, and the key value adding step. It was the gap between our basic science and the manufacturing techniques which gave the Japanese their chance. We must not repeat that mistake.

Conclusion: Our emerging tech industrial strategy

The Government set out in September 2012 our approach to industrial strategy. This focuses on looking to the future, setting out a long-term, whole of Government approach, to give business the confidence to invest and grow. We are taking action to make this happen. We are working in partnership with business to develop 11 sector strategies. Our update to the Life Science strategy was published in December, other strategies will be published between now and the summer. As well as sectors we are taking action in cross-cutting areas including technologies, skills, procurement and access to finance. Technologies and the broader research which underpins their development is a fundamental part of our approach to industrial strategy.

The UK is fortunate to have such a broad science and research base. Reed Elsevier's 2011 review of the comparative performance of the UK Research Base identifies "over four hundred niche areas of research in which the UK is distinctively strong." No other medium-sized economy has anything like that range of world-class research activity. It is not just STEM but STEAM – Science, Technology, Engineering, Arts and Maths.

One of the main aims of long-term science policy must be to maintain that breadth and not to find ourselves forced to trade off being world class in life sciences or history or physics. We do not direct our scientific and research community into particular research projects. Instead our science community rightly enjoys extraordinary autonomy as funding is largely allocated on the principle of excellence determined by academic peer review. This is the first pillar for our science and innovation policy.

After the failure of the economic interventionism of the 1970s and the triumph of the liberal revolution in economic policy of the 1980s, we are wary of government picking winners. In so far as government can raise growth, we tend to focus on measures that apply across the economy as a whole – such as deregulation or lower corporate taxes or ease of setting up a business. We perform well on many of these measures – the UK is ranked 2nd in the G7 for ease of doing business. So the second pillar is a flexible open market economy that can absorb the latest scientific advances.

Put the breadth of our science base together with the dominant intellectual climate and you get classic British policy on science and technology. We finance a broad range of research selected by scientists on the basis of its excellence. The Coalition is tearing down the barriers to the smooth functioning of a modern market economy. Strong science and flexible markets is a good combination. But, like patriotism, it is not enough. It misses out crucial stuff in the middle – real decisions on backing key technologies on their journey from the lab to the marketplace. That is the missing third pillar to any successful high-tech strategy. It is R&D and technology and engineering as distinct from pure science. It is our historic failure to back this which lies behind the familiar problems of the so-called "valley of death" between scientific discoveries and commercial applications.

We are living now with the long-term consequences of the failure to have a policy promoting backing the key technologies. Look at the business sectors where the UK is strong – creative industries, financial services, construction, new web-based services. They are all areas where innovation occurs without capital-intensive R&D. So paradoxically the very aversion to backing particular technologies with R&D has itself contributed to a change in the structure of the British economy – an economy which innovates but does not do as much R&D as many of our competitors.

Focusing on R&D and on particular technologies is not the same as picking winners, which notoriously became losers picking the pockets of tax payers. Instead the Government should focus on big general purpose technologies. Each one has implications potentially so significant that they stretch way beyond any one particular industrial sector – just as Information Technology has transformed retailing in recent years, so satellite services could deliver precision agriculture in the future.

Our research councils tend to focus on more upstream research whereas in US the National Science Foundation and the National Institute for Health go further downstream closer to market. Sometimes our approach can look like mother birds pushing their fledglings out of the nest but with too many falling to the forest floor to be eaten by foxes. We think our problem is that we lack the same willingness to take risk as in America. But often we were expecting companies to step in earlier, take more risk than in the US or elsewhere.

The Technology Strategy Board is a crucial but underestimated institution which can help plug that gap. They are working more closely than ever before with our research councils to get a more sustained support from blue skies research to closer to commercialisation. As part of the life sciences strategy, the Government set up a bioscience catalyst worth £180m split 50/50 between the Medical Research Council and the Technology Strategy Board to take new medical innovations closer to practical application. Already this scheme is a real success with new biotech start-ups emerging. In many ways, the US does things on a far more ambitious scale than us. They are more imaginative and bold in the use of procurement for example. Their support for innovative small businesses with Ronald Reagan's Small Business Research Initiative is on scale far greater than ours. Where Government has a big role such as in medicine or security they harness that. The US Orphan Drugs Programme for example provides strong incentives for drug

development. DARPA rests on the assumption that US security depends on harnessing key new technologies and they do that not just with research support but with contracts that are offered for new products at a very early stage. Indeed Silicon Valley originally grew on the back of contracts from the military for computers and IT. So there is much for us to learn from looking at how the rest of the world tackles these challenges.

There are some basic steps we can take using the convening power of government. So here is Industrial Strategy 101. You set up a leadership council probably co-chaired by a BIS minister and a senior industry figure in which researchers, businesses, perhaps regulators and major public purchasers come together. You use it to get them talking to each other confidently and frankly. Then that group might commission a trusted expert to prepare a technology road map which assesses where the relevant technologies are heading over the next five years or so, where publicly funded research is going, and what business is likely to do. Just this exercise, with no increase in public funding, can transform behaviour. Some of the big companies for example might have an HQ abroad and it means their British managers and also BIS ministers can show to them what we are doing and encourage more investment here. It can encourage businesses sitting on cash to invest when they see how it fits in alongside investment we are committed to putting in. You might go further and find that if the government puts some money up front it can get co-investment by others. It is a two-way street: business investment as well as government investment. You might find some key regulations which need to be eased or perhaps the opposite and some need to be even introduced to help give confidence a new technology can safely be adopted. Government might be more open about its procurement plans than before and more willing to go for an innovative use of a new technology not settling for the tried and tested. But crucially you have a vehicle for making this happen and building mutual trust. The quality of links between

business, the research community and government is itself a source of comparative advantage in the modern world.

Imagine that we are burying a time capsule in 2013 and are going to open it up in 2023. One possibility is that, by then, technology has developed in a way completely different than set out here. After all, we are still waiting to commute to work on a personal jet booster pack as operated by James Bond in Thunderball. There could well be new technologies which we just have not considered. We are not claiming perfect foresight. But in addition there are six real possibilities for the long-term impact of our strategy for these eight great technologies.

1. **False Dawn** We are still waiting. The analysis broadly stands but it has all taken longer than we had hoped. Robots are still trundling round the labs rather than waiting at table for us.
2. **Transmutation** The technologies have worked out the way we expected but new businesses have emerged in a more indirect route. As every romcom film shows, things rarely work out exactly as we expect. After all, ARM originated with the BBC Acorn computer project run out of Bristol.
3. **Gone abroad** The technologies develop roughly as expected, but the excitement now lies abroad. We are left with some multimillionaires who sold their ideas to foreign multinationals but not much else. Once again, we have grown the world's best corporate veal.
4. **It's here but it isn't ours** We have successfully grown the companies here so they have put down roots and we have got genuine expertise that cannot be easily shifted. But ultimately they are owned by big corporates that have their HQs elsewhere. Illumina is a happy example of this at the moment, but Autonomy currently looks like a less happy example of this phenomenon.
5. **We have grown big new companies** Just as the US has Google, Amazon, Facebook and Ebay, we have more homegrown

companies comparable to Vodafone or GSK or Rolls Royce. We get the regulations right. We have patient capital. We are the home to more top 500 companies than we are now.

6. **We are purveyors of R&D to the world** We host the world's clusters. From Formula One in Oxford / Warwick / Birmingham to Tech City in East London and space activity around Harwell, we are famous for our world-class R&D centres. The emerging economies are keen to work with us because creating a world-class university from scratch is hard. It's smarter to work with ones you have. Britain is increasingly recognized as the world's R&D lab. We have achieved our ambition of being the best place in the world to do science. Multinationals base their R&D facilities here. Smart people from around the world come and research here. We have also earned a reputation as the best managers of big international scientific projects.

No single path is certain. But the UK's record as a place with an enviable breadth of world-class research and a welcoming environment for doing business set us in a good place. Success now depends more than ever before on bridging the "valley of death" between discovery and commercialisation.

The UK's continuing strong public support for research, an improving macroeconomic environment and a new impetus for converting discovery into commercial opportunities provide good grounds for optimism. We can indeed be the best place in the world to do science.

Policy Exchange

The UK is facing global challenges. Our research is world class, but we need to be better at taking our great scientific research and applying it.

This pamphlet sets out eight great technologies where we can do exactly that:

- the big data revolution and energy-efficient computing
- satellites and commercial applications of space
- robotics and autonomous systems
- life sciences, genomics and synthetic biology
- regenerative medicine
- agri-science
- advanced materials and nano-technology
- energy and its storage

The UK's strong public support for research, the improving macroeconomic environment and a new impetus for converting discoveries into commercial opportunities provide good grounds for optimism. We can be the best place in the world to do science.

£10.00
ISBN: 978-1-907689-40-6

Policy Exchange
Clutha House
10 Storey's Gate
London SW1P 3AY

www.policyexchange.org.uk