Government Office for Science

Foresight

Technology and Innovation Futures:

UK Growth Opportunities for the 2020s– 2012 Refresh

Acknowledgements

Foresight and the Government Office for Science would like to thank those who have contributed to this report. A list of those who participated in the workshops and interviews is provided at the end of this document.

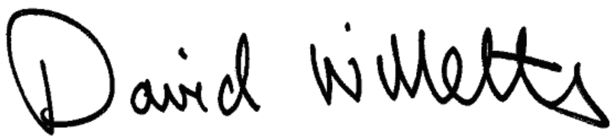
Foreword

Rt Hon. David Willetts MP, Minister for Universities and Science

It is with great pleasure that I welcome this refreshed report on *Technology and Innovation Futures* from Foresight, in the Government Office for Science. As Minister for Universities and Science, I am constantly amazed by the inventiveness of our scientists in researching and developing new and exciting technologies, which have the potential to transform lives. It is clear to me that many of these emerging technologies will play a critical role in how we all live in the future, including making a contribution to the UK's economic growth and bolstering its role as an international leader in technology innovation and creativity.

Technology is a very important stimulus for scientific advancement, driven by human curiosity, a wish to solve problems, and the desire to explore the unknown and the just possible. That is why I have taken steps to protect the science budget, to give room for scientific research to grow and develop in a dynamic and nurturing environment. The role played by the Technology Strategy Board will continue to be vital in supporting the development of new technologies and helping them reach their full potential. This government has gone further than ever before with its Industrial Strategy to identify sectors for growth, and it will continue to take the lead on generating economic growth.

My role is to champion science and technology in all its forms. This is a very long game. In 1937 the British engineer Alec Reeves laid the foundations for the modern telecommunications era with his pioneering work on digital sounds. It would be decades later that the technologies required to exploit his ideas were developed. His work ultimately enabled the Internet, digital radio and television, mobile telephones and DVDs. The lesson to be drawn from this is that, as the great Professor Stephen Hawking said during the Opening Ceremony of the London 2012 Paralympic Games, as he guided us through a journey of discovery at the wonder of science, 'Look up at the stars and not down at your feet. Try to make sense of what you see, and wonder about what makes the universe exist. Be curious...There should be no boundary to human endeavour.' In the words of Prospero, also echoed that night, 'The greatest adventure is what lies ahead.'



Technology and Innovation Futures: UK Growth Opportunities for the 2020s – 2012 Refresh

Executive summary

Technology and Innovation Futures is a forward look at a range of developments that have the potential to support sustained economic growth in the UK over the next 20 years. In 2010 interviews and workshops were undertaken with 180 representatives from industry, research, international institutions and social enterprises, and a report was published that identified 53 technologies likely to be important. In some areas the UK already has a competitive advantage; in others demand will be driven by future need or the likely size of the market.

Technology changes quickly and so do the economic and political circumstances. This 2012 refresh is an early opportunity to take stock of the 2010 findings, and see whether any new trends have emerged. Detailed, structured interviews and a survey involving experts in key areas were carried out for this refresh.

This report refreshes the original list of 53 technologies, and it was reassuring to find that in the main the technologies identified in 2010 are those that today are seen as strong candidates for growth over the next 20 years. However, several changes in emphasis have become apparent as the potential of some technologies has begun to be implemented by industry, systematised and made more readily available.

In the report published in 2010, a number of important messages were highlighted and these remain valid today. Firstly, there are strong opportunities for growth in the UK economy if businesses can harness the scientific and industrial capabilities required to take advantage of the technologies and innovation identified in the report. Secondly, the UK will undergo an energy transition during the next 10–20 years and there will be important opportunities for UK companies. Thirdly, there continues to be a critical need for a stable, coherent framework of regulation and support, so that the private sector has the confidence to invest, including in intellectual property to protect research and development and encourage investment.

So what has changed? There are new challenges of balancing an energy generation mix, which includes the potential for more emphasis on gas, tackling intermittent supply from renewable sources, and new opportunities from hybrid energy systems combined with rapidly developing battery technology.

Service robotics is highlighted as being of growing importance, whereby devices work alongside humans, adapting to contexts rather than simply repeating actions. Additive layer manufacturing (such as 3D printing) has moved from a largely research and development environment to being a core component of some industrial strategies. This links to the major breakthroughs in developing new materials and tailored medicine. There is also a stronger trend in the way that sensors, miniaturised communications and processing provide constant feedback and permanent connections to networks.

With the UK struggling with weak economic growth, it is more important than ever to invest in long-term catalysts for growth, such as science, technology and innovation. Seizing those opportunities will be a crucial part of the UK’s future economic prosperity. A critical factor in the potential for the UK to exploit any given technology will be the availability of a skilled workforce, in most cases graduates. There are already well-documented shortages in some of the areas of innovation highlighted.

The government has a core role as a facilitator of collaboration between industry and researchers, helping large and small businesses to work together and identifying common goals and strategies across sectors to leverage the UK’s advantages in technological innovation. This is the argument for the UK’s developing industrial strategy, which will play a key role in prioritising more significant investments in sectors important for the country’s future growth.

These policies are already starting to bear fruit. Universities and business schools are keener than ever before to speed up innovation processes and translate research into business ideas. Contributors to this refresh praised the work of the Technology Strategy Board in offering support to start-ups, which are a useful discovery mechanism to demonstrate the potential of an idea. Nevertheless, there is more to do in those areas where it is harder to fund the high costs of testing promising research ideas and to close the gaps between start-ups and big business. The Catapult Centres being set up across the UK will be crucial in bridging these gaps.

Contents

1. Introduction

1.1 2012 Refresh

Two years ago Foresight published the *Technology and Innovation Futures* (2010) report, identifying opportunities for future UK economic growth in the 2020s.[1] But technology changes quickly and so do the economic and political circumstances. Foresight agreed to refresh the report for the Minister of State for Universities and Science in 2012, in order to take stock of the findings in 2010, and see whether any new trends have emerged.

In reviewing the original report, it was reassuring to find that in the main the technologies identified in 2010 are those that today are seen as strong candidates for growth over the next 20 years. This is hardly surprising but does reinforce the robustness of the approach applied two years ago. However, several changes in emphasis have become apparent as the potential of some new technologies has begun to be implemented by industry, systematised and made more readily available.

Some technologies feature more strongly in this refresh than in the original report. For example, the challenges of balancing the energy generation mix have become clearer. Intermittent energy supply is seen as a major challenge, but also a possible source (or accelerator) of innovation. Hybrid energy systems, whether combined heat and power, fuel-cell and battery electric vehicles, or power plants co-generating electricity and hydrogen-based chemicals, are seen as more important in the future, while battery technology has advanced rapidly.

’Service robotics’ is highlighted as of growing importance, whereby devices work alongside humans, adapting to contexts rather than simply repeating actions. Additive layer manufacturing (such as 3D printing) has moved from a largely research and development environment to a core component of some industrial strategies.

There is also a stronger trend in the way that sensors, miniaturised communications and processing provide constant feedback and permanent connections to networks. This links to the major breakthroughs seen in developing new materials and tailored medicine. In transport and energy, the challenge is to design systems (such as multimodal transport) that take account of the behaviour of individuals and businesses.

[1] http://www.bis.gov.uk/assets/foresight/docs/general-publications/10-1252-technology-and-innovation-futures

1.2 Our approach

For this 2012 Refresh, Foresight conducted structured interviews and a survey with 15 leading academics and 26 industry experts on the 53 technology areas identified in the 2010 report. They were asked what interesting new technologies or other developments had taken place recently, or might take place over the next 10 years, that could create growth opportunities for the subsequent decade. The same questions in a survey were sent out to over 180 contributors to the original 2010 report, asking them to flag any interesting technological developments. Annex 1 contains a full list of contributors. The 53 technologies, from the 2010 Technology Annex,[2] were reappraised in blue throughout and a fresh executive summary was added.

Section 3 sets out three new themes that are emerging from individual technologies and may be important: the *energy transition* to smart grids and an energy mix that balances intermittency from growing renewable sources and the accessibility of gas *on demand*, describing how new printing technologies that are revolutionising traditional manufacturing processes and expanding the potential of regenerative medicine and *human-centred design*, where connectedness and sensors that are growing in ubiquity and generating data will be processed by increasing computing power, but challenging the designers of algorithms to harness the full potential. More detailed information on each technology can be found in the original Technology Annex of the 2010 report.

[2] http://www.bis.gov.uk/assets/foresight/docs/general-publications/10-1252an-technology-and-innovation-futures-annex.pdf

2. Potential growth areas

2.1 Biotechnological and pharmaceutical sector

GENES AND CELLS (1–6)

2.1(1) Genomics, proteomics and epigenetics

Since the discovery of DNA in 1953, scientists have sought to uncover the entire complement of genes (the genome) of organisms and especially of humans. Researchers have discovered massive numbers of genes that encode for proteins as they sequence more genomes. However, we cannot use just genomic information to understand how organisms function. For instance, an understanding of the final structural modifications to proteins, environmental factors and inherited information not encoded in DNA (epigenetic information), are all necessary to fully understand basic life processes, such as reproduction, development, disease, cellular signalling, metabolism and bioenergetics.

Genomics is the study of the entire complement of genes in an organism. A raft of genomic techniques has been developed, including microarray technology, to analyse genome-wide expression levels, and DNA sequencing technology. In 2001 the first drafts of a human genome were published.[3] However, our understanding of the human genome still remains limited. Key future issues include understanding the basis of genetic variation (and its applications to medicine) and understanding biological pathways and networks. As the cost of genome sequencing falls this may enable genomic sequences to be compared across populations, facilitating our understanding of variation. Genomic techniques are also invaluable in our study of other organisms and in the development of agricultural technologies.

The term ‘proteome’ defines the entire protein complement in a given cell, tissue or organism. In its wider sense, proteomics research also assesses protein activities, modifications and localisation, and the interactions of proteins in complexes. Proteomics is very much a technology-driven enterprise. Like genomics, the sheer scale of proteomics research makes it a community effort, with the Human Proteome Organisation (HUPO)[4]playing an important role in coordinating projects worldwide.[5,6] Furthermore, proteomics technologies are large and expensive, which means that they are not available to the whole research community. We need to find ways to allow widespread use of

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[3] http://www.nature.com/nature/journal/v409/n6822/abs/409860a0.html
[4] http://www.hupo.org/
[5] http://www.nature.com/nature/journal/v456/n7223/full/456702a.html
[6] http://www.hplusmagazine.com/articles/neuro/tweaking-your-neurons

proteomics tools.[7] The major input from proteomics studies in the short term will therefore be the identification of a particular set of biological markers (biomarkers) for a specific disease or trait. More traditional biochemical and immunological tests will then be developed based on these discoveries.[8] By studying patterns of protein content and activity, and how these change during development or in response to disease, proteomics research is poised to increase our understanding of how cells behave at the systems level. It is hoped that clinical research will also benefit from proteomics by both the identification of new drug targets and the development of new diagnostic markers.

Epigenomics is a relatively new field in which inherited epigenetic modifications, such as DNA methylation, DNA packaging and transcriptional modifications, are studied en masse. These processes often function to turn on or turn off particular genes and have been implicated in a range of diseases including cancer and neurological disorders. Knowledge transfer, expertise, reduced costs and miniaturisation of diagnostic tests will allow the utilisation of epigenomic assays to become more widespread.

Bioinformatics –advances in 'omics' have been linked to increased computing power and developments in bioinformatics, which have facilitated increasingly complex analysis of gene, protein and epigenomic function, including pattern recognition, data mining, machine learning and prediction techniques. Associated with this has been the advent of increasingly large and complex datasets with the associated challenges of managing the wealth of information produced. It depends on publicly accessible databases that use agreed standards to describe data, allowing comparison and integration.

Metagenomic approaches to identify genomic signatures from mixed populations of microorganisms, many of which may be unculturable, may become more commonplace for identification of signatures for environmental monitoring or bioprospecting. Developments in bioinformatics will greatly aide these approaches.

2.1(2) Nucleic acids

Nucleic acid technologies comprise a suite of technologies for diagnostics, manipulation and intervention in biological systems. Advances in this field have been driven by an increased understanding of the relationship between DNA and RNA, and the complexity of gene regulation, as well as high-throughput, low-cost techniques that have allowed a shift from studying individual functions of genes to global investigations of cellular activity. Further developments are likely as our understanding of genomics, epigenomics, proteomics and microbiomics develops, with the

[7] http://www.nature.com/nature/insights/6928.html
[8] http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1579414

miniaturisation of multiple laboratory functions through lab-on-a-chip (LOC) technology, and as the cost of techniques such as gene sequencing continue to fall.

Nucleic acid technologies are used for a range of applications including gene expression profiling, diagnostics, disease characterisation, toxicology, drug development and gene therapy. Nucleic acid probes and diagnostic microarray systems can detect the nucleic acid sequence or sequences that identify a specific infectious disease agent, human genetic disease or individual (DNA profiling). Advances in microarray technology have allowed a shift from studying individual functions of genes to global investigations of cellular activity. For example, genotyping technology can identify blocks of DNA associated with phenotypic traits that help in the location of disease genes. This information aids the understanding of gene regulation, cell proliferation and disease progression. Microarray technologies now provide the potential to develop sensitive diagnostic tests and less toxic individually tailored therapeutics.[9]

2.1(3) Synthetic biology

Synthetic biology is an emerging area of research that involves the design and construction of novel artificial biological pathways, organisms or devices, or the redesign of existing natural biological systems. The application of engineering principles to the design and construction of complex biological systems is likely to provide a step-change from the 'tweaking' of existing genomes, usually described as genetic engineering.

Although in its infancy at present, synthetic biology has the potential to drive industry, research and employment in the life sciences in a way that could rival the development of the computer industry from the 1970s to the 1990s. The global synthetic biology market is expected to reach $16.7 billion by 2018.[10]Synthetic biology offers considerable opportunities, there arealso concerns around potential misuse, in particular the generation of novel pathogens or modification of existing ones to increase virulence or defeat medical countermeasures.

Synthetic biology encapsulates a range of approaches, from top-down redesign of whole bacteria, to bottom-up assembly of new species (although this has yet to be achieved). The concept that has shown the greatest early promise is fashioning bacteria into 'biofactories'to produce specific chemicals or biological compounds. For example, the Lawrence Berkeley National Laboratory in the USA has engineered bacteria to produce artemisinin, a compound

[9] Foresight Horizon Scanning Centre Sigma Scan 2008 www.sigmascan.org, paper 468, 'Advances in DNA Microarray Technology'
[10]http://www.prnewswire.co.uk/news-releases/synthetic-biology-market-is-expected-to-reach-usd-167-billion-globally-in-2018-transparency-market-research-166861966.html

used to treat malaria.[11]Artemisinin is found naturally in the wormwood plant but is costly to synthesise chemically or harvest. The same methods could theoretically be used to produce cancer drugs, such as paclitaxel, that are currently expensive. Applications are not, however, limited to producing pharmaceuticals more cheaply; food, energy, materials and structures are also envisaged, as are other uses such as biosensing, decontaminating polluted land and water, and processing information.

Others are working on the construction of standardised sequences of DNAthat could be assembled to produce predictable effects, or a cell that signals how many times it has divided. A registry of biological parts has been set up at the Massachusetts Institute of Technology that aims to produce a library of standard genetic components (called 'bioparts') that can reliably perform a specific function and be connected to form novel genetic circuits.[12] These projects will lead to new tools and methods in synthetic biology in the next 3–10 years and will set the stage for future applications. We can expect to see new technologies in the next 10–20 years.[13] The UK has recently published a roadmap for synthetic biology, and the Technology Strategy Board and the research councils plan further investments[14], including the recent announcement of an Innovation and Knowledge centre in Synthetic Biology.[15][16]

2.1(4) Stratified and tailored medicine

Knowledge of individual and population-level genomic and environmental data will allow tailored diagnosis, treatment and prevention of disease. Advances in fields such as epidemiology, computation, imaging, sensing and pharmacology will lead to cost-effective and efficient health management. The NHS, healthcare and pharmaceutical industries may be key to the success of predictive health management in the UK.

Current models for treating disease are based around the empirical prescription of drugs. While some drugs are effective for a wide range of the population, many show varying effects in different individuals and population groups. As our understanding of the underlying basis of disease and disease response improves, there will be an increased opportunity to target medicine to those individuals who would benefit from treatment.

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[11] Foresight Horizon Scanning Centre Sigma Scan 2008, www.sigmascan.org, paper 531, 'Promising Applications of Synthetic Biology'
[12]http://openwetware.org/wiki/The_BioBricks_Foundation
[13]Foresight Horizon Scanning Centre Sigma Scan 2008 www.sigmascan.org, paper 531, 'Promising Applications of Synthetic Biology'
[14]http://www.innovateuk.org/content/news/synthetic-biology-roadmap-.ashx
[15]http://www.bis.gov.uk/news/speeches/vince-cable-industrial-strategy-september-2012
[16]http://www.innovateuk.org/content/news/synthetic-biology-roadmap-.ashx

Many disease traits have a genetic component. Certain diseases, such as cystic fibrosis, can result from a mutation within a single gene. Other diseases are more complex, with multiple genes contributing to the disease. Furthermore, there is an increased recognition that environmental and epigenetic factors can alter both the manifestation of disease and an individual's ability to respond to treatment. Biomarkers have been used to detect these variances, and combinations of biomarkers can be used to build a picture of an individual's susceptibility to a disease or drug. Gathering information on the association of biomarkers with disease across populations, and the corresponding effectiveness of drug treatment, can allow treatment to be used appropriately, a technique called stratified medicine. As further biomarkers are developed and population data are acquired, it will become increasingly possible to analyse an individual for certain biomarkers to determine the best course of treatment.

Personalised medicine follows a similar principle to stratified medicine, in that it requires knowledge of an individual's genetic, epigenetic and environmental make-up. However, here the individual is either directly tested for known biomarkers or, more interestingly, can have defective cells screened and compared with normal cells from the same individual or tissue. In the case of cancer, this allows treatment to be tailored by gaining an understanding of the underlying cause of cancer in that individual.

Concerns over the adoption of these techniques surround the large-scale collation of data and risks of misuse thereof. There are ethical questions over pre-determination by genetic data.

2.1(5) Stem cells

Stem cells are 'proto-cells' capable of growing into the full range of specialised tissue (e.g. nervous, muscular, connective) found in adults. Laboratory studies of stem cells enable scientists to learn about the cells' essential properties and what makes them different from specialised cell types. Scientists are already using stem cells in the laboratory to screen new drugs, cure some forms of blindness and develop model systems to study normal growth and identify the causes of birth defects. Research on stem cells continues to advance knowledge about how an organism develops from a single cell and how healthy cells replace damaged cells in adult organisms. While adult stem cells have been used to treat disease for several decades in bone marrow transplants, it is the potential progress in embryonic stem cell research that has been the source of great therapeutic hope, ethical and legal controversy, and international competition.

Despite successful treatments such as the tissue-engineered trachea,[17] there is concern about delivery mechanisms, regulation and the costs of such treatments. At this relatively early stage in our understanding of stem cells, there are also uncertainties about the way stem cell treatments actually work and concerns over the safety of some treatments (for example, some have resulted in the development of tumours) – all of which requires further consideration as the science develops. Despite these challenges, the UK is likely to benefit from advances in the sector, which could be encouraged through adapted regulation and the development of new business models.

Embryonic stem cell research has benefited from the UK's regulatory position, which has allowed publicly funded research on certain human stem cell lines since 2002 – in the USA embryonic stem cell research took place only in the private domain until new legislation was enacted in 2009.[18] There is a risk that changes to US legislation, as well as inconsistencies in global regulation and research strengths, might affect the UK in the long term.[19] There is increasing competition globally particularly from the emerging BRIC economies (Brazil, Russia, India and China).Japan is widely recognised for its induced pluripotent stem cells (iPS) research.[20]

There may be an opportunity for the UK to take a proactive stance in developing new markets around both 'allogeneic' stem cells (whereby cells are taken from a genetically similar donor) and 'autologous' stem cells (whereby cells are taken from the host, re-engineered and re-implanted). The former might eventually involve the development of a service model similar to that used by the blood donor industry. The remit of the UK Stem Cell Bank might be extended to support such a development, if regulatory hurdles could be overcome, particularly if there was support from the NHS. The UK's strength in health services and the high standards of its healthcare would place it in a good position to compete in the international market of autologous stem cells.

The sector has made robust progress since 2010. Cell-based therapies, whether using stem cells or genetically manipulated cells, continue to progress towards cures for many unmet medical needs. The field is 'moving from the exploration to the exploitation phase', with the cell therapy industry having revenues of over $1 billion in 2011 and landmark commercial deals such as Shire's acquisition of Advanced BioHealing for $750 million.[21] The first 'blockbuster', Dendreon's prostate cancer therapy (Provenge), alone accounted for $280million in revenue in its first year.

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[17] http://www.thelancet.com/journals/lancet/article/PIIS0140-6736(12)60737-5/abstract
[18] http://www.nature.com/ncb/journal/v12/n7/full/ncb0710-627.html
[19] http://www.aaas.org/spp/sfrl/projects/stem/report.pdf
[20] http://www.nistep.go.jp/achiev/ftx/eng/stfc/stt032e/qr32pdf/STTqr3201.pdf
[21] http://www.sistemic.co.uk/storage/EBR%20Summer%202011%20p24.pdf

The UK is still at the forefront of much of the translation in this area, with University College London a leading global centre.[22] The UK regulatory environment is also supportive. However, the picture is clouded by an exemption agreed to EU regulation in the area, which is being used by a number of other countries to allow cell treatment practitioners to avoid the cost of undertaking clinical trials. The exemption, which was not intended to be applied in this way, is having a negative impact on the market for therapies that have undergone the full trial process, resulting in far fewer companies being active in the EU than in the USA. A verdict from the European Court of Justice, that any patent depending even indirectly on human embryonic stem cell lines is outlawed on moral grounds throughout the EU,is similarly likely to result in fewer companies being active in the EU.

Global progress on cell therapies has been rapid. Today there are over 300 commercially sponsored clinical trials including those for diabetes, cardiovascular disease and stroke.[23] There are also over 1000 clinician-led trials underway.

2.1(6) Regenerative medicine and tissue engineering

One of the major components of 'regenerative medicine', tissue engineering, follows the principles of cell transplantation, materials science and engineering towards the development of biological substitutes that can restore and maintain normal function. Tissue engineering has a wide range of applications in biomedicine, including in vitro construction of whole organs, in vivo tissue and wound repair, and insitu screening as a replacement for animal testing. The current cost of tissue engineering prohibits widespread adoption of medical technology. Regulatory and ethical barriers can delay the commercialisation of new products.

Insitu tissue regeneration material is implanted directly in the body and regenerates the tissue over time as the material degrades. Cells are seeded onto materials and implanted directly. The seeded cells are not expected to survive for long but to deliver factors to encourage dormant cells to repair/regenerate damaged tissue.

Tissue engineering material can act as temporary scaffold for cell culture and tissue growth in vitro. The tissue-engineered construct can then be implanted as a material/tissue composite, or the material can be degraded so that only tissue is implanted. Stem cells are potentially ideal for tissue engineering as they can be manipulated in vitro to produce a range of differentiated cell types. The use of autologous stem cells taken from a host and re-implanted would potentially reduce immunogenic issues with transplantation.

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[22] http://www.ucl.ac.uk/cell-gene-therapy/
[23] http://www.futuremedicine.com/doi/pdf/10.2217/rme.12.45

Biomaterials:typical approaches to tissue engineering utilise three types of biomaterial as scaffolds: (1) naturally derived materials, e.g. collagen and alginate; (2) acellular tissue matrices – e.g. bladder submucosa and small intestinal submucosa; and (3) synthetic polymers – e.g. polyglycolic acid (PGA), polylactic acid (PLA) and poly(lactic-co-glycolic acid) (PLGA). A key issue with biomaterials is designing robust, reproducible and biocompatible scaffolds. Naturally derived materials and acellular tissue matrices have the potential advantage of biological recognition. However, synthetic polymers can be made reproducibly on a large scale with controlled properties of strength, degradation rate and microstructure.

Automation Techniques:micro-masonry[24] and 3D organ printing techniques[25] use different methods of automating the construction of 3D structures. Micromasonry is a biocompatible method for construction of 3D structures that works by laying down cells encapsulated in cubes allowing 'Lego-like' construction on a matrix. Organ printing sequentially layers gels, cells or aggregates onto gel paper to build a 3D structure. The gel is then dissolved to give rise to the functional organ.

SENSORS AND COMPUTING (7–12)

2.1(7) Lab-on-a-chip

LOC devices integrate and scale down biomedical and other analytical laboratory functions and processes to a miniaturised chip format. Their small size and low power requirements, and the speed at which they provide results, offer possibilities for moving many diagnostic and analytical activities out of fixed, centralised, facilities and provide real-time information to, for example, health staff at surgeries and other remote locations. LOCs are therefore an important component of 'e-health', as well as having many non-health applications, such as pollution and contamination monitoring. Applications of LOC devices include rapid insitu detection, clinical diagnosis, forensic science, electrophoresis, flow cytometry, blood chemistry analysis, and protein and DNA analysis.

The devices can be fabricated from many types of material including polymers, glass, silicon or combinations of these. A broad range of fabrication technologies are used for LOC devices. LOC systems have several common features, including microfluidics and optical or electrochemical sensing. Microfluidics deals with fluid flow in tiny channels using flow control devices (e.g. channels, pumps, mixers and valves). Progress in microfluidics – one of the key engineering challenges of the early 21st century – will enable fabrication of LOCs to analyse and control biochemical systems.

[24] http://onlinelibrary.wiley.com/doi/10.1002/adma.200903893/abstract
[25] http://ukpmc.ac.uk/abstract/MED/12679063/reload=0;jsessionid=vHBUGfz8dg5xsrC5kxfS.12

2.1(8) Medical and bioimaging

Medical imaging plays a vital role in the diagnosis and treatment of disease, as well as enabling scientific research. Radiology uses radioactive substances and electromagnetic and sound waves to develop images of structures within the body. Advances in imaging techniques, including brain imaging, may provide opportunities for improved diagnosis and monitoring.

Radiology encompasses a range of non-invasive techniques from the familiar X-ray and ultrasound during pregnancy to advanced magnetic resonance imaging (MRI) and positron emission tomography (PET). Advances in medical imaging, computation and visualisation techniques have led to increased resolutions and the development of 3D imaging techniques. Further developments will lead to improved abilities to image and reconstruct 3D models and allow more detailed information to be extracted from each image. For instance, fluorescence-assisted resection and exploration (FLARE) technologies,[26] which combine both visible light imaging with near-infrared imaging of fluorescent biomarkers, can detect particular pathologies associated with tumours without the need for biopsy. Similarly, colour X-ray or tomographic energy-dispersive diffraction imaging (TEDDI) can be used to biopsy tissues by utilising scattered X-rays to build a spatially resolved picture that can distinguish between different materials.

While medical imaging has been successfully applied to the treatment of many forms of disease, the diagnosis of neurological diseases and disorders is still in its infancy. Advances in understanding how the brain functions, coupled with improved in vivo neuroimaging, both the tissue and the cellular level, could yield healthcare benefits through, for example, improved diagnosis and condition monitoring of physical and mental states.

The development of microscopes that can image beyond the diffraction limit of light (super-resolution microscopes and atomic force microscopes) or that can image the human body in vast detail (high strength MRI) is also likely to make a significant contribution to advances in to the agriculture/food and drink sector as exemplified above, a sector which is the largest manufacturing sector in the UK. The impact of bioimaging in relation to Alzheimer's disease could benefit the NHS by hundreds of millions of pounds leaving aside the social benefits that would stem from a greater understanding of the disease itself.

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[26] http://www.siemens.com/innovation/pool/en/publikationen/publications_pof/pof_fall_2008/early_detection/imaging/pof208_med_imaging_pdf_en.pdf

2.1(9) Performance-enhancing pharmaceuticals

Advances in our understanding of brain function are likely to provide a better understanding of mental health. They could also lead to new treatments for, for example, neurodegenerative conditions such as dementia and provide a better understanding of the effects of legal and illegal so-called 'recreational' drugs on different people and how to treat addiction. Other possibilities include 'cognition enhancers': substances that enhance the performance of our brain in specific ways, such as improving short-term memory and increasing our speed of thought.[27] Enhancement through lifestyle drugs may well become the norm, thanks in part to a wealth of drugs currently being developed to counter Alzheimer's disease and other problems connected with age and cognitive function.

'Emoticeuticals', drugs that act by changing hormone levels in the body, may mediate our responses in our private lives and work. 'Sensoceuticals' might enhance pleasure by restoring or accentuating the senses. Scientists have even predicted the advent of a drug that mimics the positive-feeling effects of alcohol without its drawbacks.[28]

2.1(10) e-Health

e-Health technologies include tools for health authorities and professionals as well as personalised health systems for patients and citizens. Examples include health information networks, electronic health records, tele-medicine services, personal wearable and portable mobile devices, health portals and other tools that assist in health monitoring, diagnosis and treatment. e-Health may help to deliver better care for less money.

e-Health has applications in the expansion of a personalised system of medicine in which access to medical information and diagnostics is available at home and on the move, including via mobile devices. Combined with home monitoring systems, this could enhance preventative and responsive care for vulnerable people. LOC technologies could also bring diagnostics down to the personal level, at which patients can test themselves and transmit data electronically for analysis and treatment.

The gains in quality of care, provided at lower cost, that e-health may deliver are important in a context in which health expenditure in Europe is expected to increase from 9% of gross domestic product (GDP) at present to around 16% by 2020 on account of ageing populations with more patients with chronic disease and higher expectations for healthcare.[29] The Whole

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[27] http://www.bis.gov.uk/files/file15385.pdf and http://www.bis.gov.uk/assets/foresight/docs/brain-science/bsad-review
[28] Foresight Horizon Scanning Centre Sigma Scan 2008 www.sigmascan.org, paper 511 'Growing Market for 'Lifestyle' Drugs'
[29] http://ec.europa.eu/enterprise/policies/innovation/files/lead-market-initiative/1ehealth_en.pdf

System Demonstrator programme, run by the Department of Health, suggests that ‘if used correctly e-health can deliver a 15% reduction in accident and emergency unit visits, a 20% reduction in emergency admissions, a 14% reduction in elective admissions, a 14% reduction in bed days and an 8% reduction in tariff costs. More strikingly they also demonstrate a 45% reduction in mortality rates.[30]

2.1(11) Modelling human behaviour

Our increasing understanding of human behaviour and society, and our increasing ability to model it, will increasingly allow computing power to be used to display complex relationships, and to present and evaluate alternative options. This should allow the social sciences to complement economics as a source of evidence and analysis underpinning policy and other decision making.

Understanding complex relationships, such as the links among diet, lifestyle and physical health, or those among environment, education, life experience and mental health, relies on identifying and quantifying the sources of variation. Developments in mathematics, modelling and simulation will in turn make the visualisation and comprehension of complex relationships more tractable. The applications of these techniques are widespread, including greater use of modelling in place of animal testing; use of social identity theory in conflict management, and simulations and gaming in contingency planning; and better informed decisions by individuals and institutions.

Quantitative analysis methods in social sciences that use statistical and numerical rather than verbal data have been limited, not just by the costs of gathering data but also by the amount of data that can be processed. Researchers have typically relied on small sets of data. As a result, they have tended to use the same information in many different circumstances. Computer simulations that borrow methods from applied physics make it much easier to use a greater range of information and to more thoroughly evaluate each alternative.

The big challenge, however, will be to develop statistical techniques for finding patterns in these huge datasets. Much quantitative analysis does not yet take account of insights from complexity theory, but this is likely to change as simulations that harness techniques such as agent-based modelling demonstrate their power. Because agent-based modelling involves developing rules about the behaviour of individuals in a system, quantitative and qualitative approaches may eventually merge.

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[30]http://www.dh.gov.uk/prod_consum_dh/groups/dh_digitalassets/documents/digitalasset/dh_131689.pdf

These analytical tools show promise in areas such as modelling urban growth, traffic modelling and the testing of interventions to reduce congestion, overcrowding and crime, the rise and fall of housing markets, and the growth of clusters of small, high-tech industries.[31] In all cases, the challenge will be to be certain that our understanding of human behaviour (both individual and collective), and our ability to capture that understanding in computer code or in sets of rules, is sufficient for the intended use of the model.

2.1(12) Brain–computer interface

Direct connections between a human being's nervous system and external devices, including computers, are already occurring routinely in laboratories around the world. However, there is great potential for their use becoming widespread in order to repair, assist or augment human cognitive or sensory–motor functions. This has implications for all aspects of life and work.

A brain–computer interface(BCI), which may alternatively be referred to as a direct neural interface or a brain–machine interface, is defined as a direct communication pathway between the brain or nervous system of a human or animal (or cultures of neural cells or neural networks in cultures) and an external device, which is usually a computer. In the wider field of neuroprosthetics, the connection can occur between any part of the nervous system (such as peripheral nerves, for example) and a device. The techniques for measuring brain activity comprise non-invasive, partially invasive and invasive techniques. BCIs can be used to help repair, assist or augment human cognitive or sensory–motor functions. Early experimental applications include a brain–controlled helicopter[32] and legs[33]. It should be noted that there is a growing concern over the potential vulnerability of such systems to hacking.

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[31] Foresight Horizon Scanning Centre Sigma Scan 2008 www.sigmascan.org, paper 435, 'Quantitative Simulation for Social Prediction'
[32] http://www.newscientist.com/blogs/onepercent/2012/08/thought-controlled-quadcopter.html
[33] http://www.wired.com/wiredscience/2012/09/brain-controlled-robotic-legs/

PRODUCTION (13–14)

2.1(13) Agricultural technologies

The global population is set to increase from 6.9 billion people in 2010 to 8.3 billion in 2030 according to United Nations' mid-range predictions, with the UK population set to grow by 9.8% to 68 million people.[34] The rising population poses significant challenges to global agricultural productivity, compounded by increased competition for land, water and energy. To date, technology has enabled per capita food production to increase despite a decline in the availability of land.[35] However, new agricultural technologies are likely to be required to meet future demands. Agricultural technologies range from novel farming techniques to third-generation crops.

Already important in the agri-food industry, biotechnology continues to generate new tools and techniques based on molecular and genomic approaches to food, nutrition, health and well-being. Biotechnology offers the potential for greater efficiency for producers and processors, as well as additional benefits for consumers. In foods, biotechnology may allow better and more efficient use of raw materials and by-products, through improved and novel enzymes and microbes optimised for fermentation. Biotechnology could also improve food safety and ensure traceability across the food chain. For example, state-of-the-art polymerase chain reaction based tests will radically cut the time it takes to find and identify pathogenic bacteria in food, while increasing the sensitivity with which pathogens can be detected.[36]

Genetically modified (GM) agricultural technologies fall into two main categories, according to the crop traits that are targeted:

Inputtraits: existing commercial GM crops traits include herbicide tolerance and insect resistance, utilising non-plant genes, for example glyphosate for herbicide tolerance and Bt (genes from the soil bacterium *Bacillus thuringiensis)* for insect resistance. New approaches will extend the current technologies to a wider range of crops and develop newer traits, such as tolerance to herbicides other than glyphosate and glufosinate (for exampledicamba), resistance to a wider range of pests and diseases (for example fungus-resistant potatoes, nematode-resistant soybeans), and improved utilisation of nutrients such as fertilisers.

Output traits: this encompasses agronomic traits that improve plants' ability to withstand stresses, such as drought, salt and cold, and improves their photosynthetic capacity. Drought-tolerant maize, in particular, is an emerging area, with hybrid strains commercialised in the USA and expected in Africa

[34] http://unesdoc.unesco.org/images/0021/002154/215492e.pdf
[35] http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter8.pdf
[36] http://www.inea.it/public/pdf_articoli/1159.pdf

by 2017.[37] This approach includes modification of plants to change their quality characteristics to give a higher value product, such as a higher content of omega 3, higher levels of vitamins, suitable for the production of plastics, improved animal feed value (altered protein, lysine and phytase contents), enhanced starch content and improved suitability for use as biofuels.

Biotechnologists also anticipate so-called second- or third-generation products. The term s*econd generation* usually describes the development of newer input traits targeted at pests, diseases and weeds, as well as some of the output traits closest to commercialisation such as altered oil profiles in some oilseeds and crops with improved ability to produce desirable starches. *Third-generation* products tend to include those furthest from commercialisation and include the agronomic traits targeted at improving the ability of plants to withstand environmental stresses.

To meet UK CO_2 emission targets it will be necessary to decarbonise agriculture. Approaches could include the use of engineered feed stocks to reduce CO_2 emissions from livestock; conversion of CO_2 to methane fuel; the use of biowaste to synthesise biogas and syngas though anaerobic digestion; the use of algae to mop up CO_2;development of long-life food to allow low-carbon transport; and recycling of waste to produce non-petroleum-based fertilisers.

New farming approaches could also alter our dependence on traditional farming methods. These include precision farming, in which farming techniques are applied at a microclimate level,for example plants are fed only the nutrients and water they need at the time they need it, and vertically integrated agriculture, in which large-scale agriculture occurs in high-rise structures minimising land requirements.

In the coming years the maturing field of nanotechnology is likely to bring radical new products and approaches to assist crop production and storage (including packaging). Exploiting a convergence of nanotechnologies, genomics and microelectronics, new diagnostic tools for animal and plant diseases are dramatically improving our capacity to detect and monitor the spread of plant and animal diseases. Already today, nanotechnologies have delivered improvements to pesticide delivery through encapsulation and controlled release methods. Capsules can remain inert until the make contact with leaves or insect digestive tracts, at which point they release the pesticide. In combination with the use of nanoemulsions, pesticides can be applied more easily and safely. Smart sensors, applied to the field, may in future allow early detection of disease, phenotypes fed back to animal and plant breeders, and monitoring of soil conditions to improve the impact of water, fertilisers and pesticides.[38] However, as with any new technology, the potential risks (on human health and the environment) must be investigated and weighed against the benefits.

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[37] http://www.isaaa.org/resources/publications/briefs/37/download/isaaa-brief-37-2007.pdf
[38] ftp://ftp.cordis.europa.eu/pub/nanotechnology/docs/nanotechnology_in_agriculture_and_food.pdf

2.1(14) Industrial biotechnology

Industrial biotechnology involves the use of biological resources to produce and process materials, chemicals and energy.[39] A range of molecular biology and engineering techniques are used to develop processes for large-scale manufacture of products such as enzymes and chemicals. These processes can be applied across the full range of manufacturing sectors, with key growth markets including speciality and fine chemicals and energy.[40]

Eight emerging technology areas underpin the uptake of industrial biotechnology: screening for new biocatalysts in nature; enzyme engineering; enzyme stabilisation and immobilisation; engineered cell factories; plant biofactories; novel processes/industrial scaling; biorefining and very large-scale bioprocessing (VLSB); and meso-scale manufacturing.

The revolution in genomics, particularly the increase in genomic sequence data resulting from high-throughput gene-sequencing techniques, is revealing a huge untapped reservoir of gene sequences that might encode for useful enzymes. New biocatalysts resulting from genomics approaches require complementary computational approaches and high-throughput screening technologies in order rapidly identify the best candidate enzymes. The UK's academic and industrial base is well placed to develop this area further, having invested in studies of a wide variety of novel biocatalysts from a range of terrestrial and marine environments.[41]

Industrial biotechnology is poised to become even more commercially significant by facilitating the processes that convert simple, inexpensive renewable feedstock into an increasing number of end products. The shift over the next 7–15 years, from trial and error to a knowledge-based approach, in which a much higher level of prediction can be incorporated into product manufacture, represents a significant commercial opportunity for the UK, drawing on the country's industrial and academic skill base in both the life sciences and materials technology.

As part of increasing sustainability, the ultimate goal of the biofactory would be to make direct use of sunlight, CO_2 and cheap inorganic nutrients to produce chemicals in plants. As the synthetic biology of microbes develops, similar approaches will be applied to the engineering of plant metabolism, building on successes in the manipulation of speciality oils and starches.

Biorefining is the co-production of a range of fuels and chemicals from biomass. First-generation biorefineries operate throughout the world for the production of bioethanol, producing 17 million gallons in 2008. Bioethanol, however, is not an ideal fuel for motor vehicles. It is corrosive and is generally produced from the edible portions of plants. Second- and third-generation biorefineries could produce more tractable, higher octane fuels from the non-edible portions of plants or algae, as well as

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[39] http://www.berr.gov.uk/files/file51144.pdf
[40] Ibidem
[41] http://www.biomedcentral.com/content/pdf/1475-2859-7-27.pdf

a variety of useful co-products that currently can be derived only from hydrocarbons. Possessing both a strong academic base in biocatalysis and a wealth of conventional refining technology, the UK is well placed to become a leader in these areas of VLSB.

2.2 Materials and nanotechnology

ADVANCED MATERIALS (1–5)

2.2(1) Nanotechnologies

Nanotechnologies involve the manipulation of matter at a scale ranging from 1 to 100 nanometres. This is a scale comparable to individual molecules. At such scales the familiar laws of physics of the everyday world do not apply, and instead quantum mechanics determines both the constraints and the opportunities of nanotechnologies.[42]

In the shortterm, nanotechnologies could yield smaller, faster computers and sharper, more efficient electronic displays. Putting nanoparticles into paints could reduce their weight. Used on aircraft, this could reduce the total weight by 20%, lowering fuel consumption. Nanoparticles could help to keep the environment clean. Researchers are studying the ability of nanoparticles to transform hazardous chemicals found in soil and groundwater into harmless compounds.

Major medical applications are likely to be longer term. Nanoparticles could deliver drugs to specific parts of the body. They could also be used in lightweight, long-lasting implants, such as heart valves and hip replacements. The development of intelligent clothing that monitors the wearer's blood pressure and heart rate and detects dangerous chemicals in the environment is also possible.

Other potential longerterm applications include nano-engineered membranes to create more energy-efficient water purification processes, longerlasting lubricants and higher performance engines.[43] For example, nano-scale porous membranes could dramatically improve the efficiency and reduce the size and energy consumption of water desalination plants. Nano-scale porous ceramic sponges can remove industrial contaminants such as mercury from waste streams. Nano-scalebiofilters may be able to remove bacteria, viruses and prions. Nano-scale

[42]Foresight Horizon Scanning Centre Sigma Scan 2012 www.sigmascan.orgPaper No 304, 'Nanotechnologies Transform Computing, Materials Science and Medicine'
[43] http://royalsociety.org/page.asp?id=1215

purification, disinfection and measurement are expected to become the standard in municipal, industrial and domestic water and wastewater treatment, potentially offering less expensive, more effective and smaller purification plants.[44]

2.2(2) Nanomaterials

In the last few years London has established itself as a world-leading centre for nanomaterials research.[45] The physical properties of nanoparticles are deliberately tuned, giving them broad potential applications in catalysis, electronic devices and medicine. There are, however, some grounds for caution in developing these uses, as nanoparticles may have an uncertain impact on health and the environment.

2.2(3) Carbon nanotubes and graphene

A range of carbon-based nanomaterials exists with applications in molecular electronics,[46] sensing, micro- and nano-electronic mechanical systems, and energy.[47] There is also potential for new composite materials in, for example, the aerospace industry, although difficulties in fabrication currently present significant barriers to their adoption.

2.2(4) Intelligent polymers ('plastic electronics')

Electronic polymers that combine electrical conductivity with plastic's benefits of flexibility, lightness and cheapness (often referred to as 'plastic electronics') offer the potential for new, thin energy-efficient displays that could even be wearable or act as e-paper. Without the need for expensive vacuum facilities, manufacturing costs for electronic polymers should be nearer those of the plastics industry than those of traditional semiconductors. Plastic electronics have applications in a wide range of computer and sensing technologies, displays and communication systems. Two other types of 'intelligent' polymers may be a source of design innovation over the coming decade, especially in the biomedical field.

Electroactive polymers (EAPs): materials that change size or shape in response to an electrical current. These polymers have been used to make motion-producing 'artificial muscle', a material that contracts in response to an electric current. Artificial muscle may replace electric motors in some

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[44]Foresight Horizon Scanning Centre Sigma Scan 2008 www.sigmascan.org, paper 550, 'Nanotechnologies for water purification'Water Purification'
[45]http://www.thomasyoungcentre.org/about-tyc/
[46]http://www.idtechex.com/research/reports/carbon-nanotubes-and-graphene-for-electronics-applications-2011-2021-000273.asp
[47]http://www.ncbi.nlm.nih.gov/pubmed/21419868

applications because it offers advantages in size, weight and manufacturing cost. Applications for springs, pumps, coatings, loudspeakers and small motors have been tested, with particular attention being given to biomedical applications.

Shape-memory polymers (SMPs): materials that remember their original shape after being stressed. Metal alloys that have 'memory' have been known since the 1930s, but research on SMPs since the 1980s has shown the latter to have greater manipulability and ease of production than alloys. These polymers can revert back to an original shape when exposed to heat or to ultraviolet radiation.[48]

Organic light-emitting diodes (OLEDs) orpolymers (OLEPs):in the field of lighting, interest has been sparked around displays based on OLEDs. These technologies are relatively inexpensive to manufacture, efficient, have flexible properties and can emit light from the near ultraviolet to the near infrared.[49]

2.2(5) Metal organic frameworks

Metal organic frameworks (MOFs) are one of a number of candidates for hydrogen and CO2 storage. The accessible bulk volume and shape of MOFs make them an interesting option for catalysis.The antibacterial market could also grow very large, including packaging, surface coatings, healthcare applications, if efficacy, safety and cost effectiveness is proven.

APPLICATIONS (6–11)

2.2(6) Smart (multifunctional) and biometric materials

Smart or multifunctional materials are designed to interact with their environment. Applications include materials that self-repair, sunglasses that darken on exposure to light, and engines that sense problems before they malfunction. The development of new materials and applications, combined with the integration of sensor technology, will generate new opportunities to transform the way everyday objects function and to produce novel medical and engineering applications.

Some smart materials are engineered to perform specific tasks and are simply high-performance materials, such as the genetically engineered dragline spider silk used for super-strong, super-light military uniforms. But the smart materials that are likely to have the most impact are those that sense changes in the environment react to them and even signal their state, in other words materials that function as both sensors and actuators.

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[48] http://www.signtific.org/en/forecasts/intelligent-polymers-biomedical-and-other-uses
[49] http://phyast4.leeds.ac.uk/pages/ScienceElectronicPolymers

A variety of materials can be utilised as smart materials, including thermochromatic materials that change colour according to temperature, magnetorheological materials, fluids that become solids on exposure to a magnetic field, piezoelectronic materials that generate electric currents on mechanical stress, and SMPs that form different structures when exposed to varying stimuli, such as heat or light.[50] SMPs also enable self-repair, for instance to repair damageto a car bonnet from heat exposure.

Smart materials have a range of applications across fields from construction to medicine and electronics. For instance, SMPs have been used to create stents that expand on exposure to body heat to open up arteries. In electronics, technologies have been developed for the active disassembly of electronic waste, with environmental benefits.

Biomimetic materials imitate nature. The aim is to understand how nature produces a useful structure or function and then artificially reproduce it. The underpinning idea is that evolution has caused plants and animals to become highly efficient. Well-known examples include basing designs on the structure of seashells, imitating the skin of dolphins for boat hulls, and water-repellent paint based upon the surface of lotus flowers. Polymer-based solar cells inspired by photosynthesis in plants are another example. Interdisciplinary approaches are required to understand and then exploit such properties.[51]

Military scientists are attempting to recreate the properties of the scales of the grey birchir, an African freshwater fish, to produce a material that can withstand penetrating impacts[52] yet remain light and flexible enough for dynamic movement, for application in a bulletproof T-shirt.

Elsewhere, aerospace engineers at the University of Bristol are mimicking the healing processes found in nature to create aircraft that mend themselves automatically during flight.[53] Imitating how a scab stops bleeding, a hardening epoxy resin is released from embedded capsules to seal cracks and restore a plane's structural integrity. Researchers are also working with a manufacturer of aerospace composites to develop a system in which the healing agent moves around a plane as part of an integrated network. There are at present, concerns about the weight and cost of these technologies.

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[50] http://85.185.231.196/mekanik/Handbook%20of%20Materials%20Selection%20-%20Kutz,Myer/smart%20materials.pdf
[51] http://www.sciencedaily.com/releases/2012/07/120717100117.htm
[52] http://web.mit.edu/cortiz/www/nmat2262.pdf
[53] http://iopscience.iop.org/1748-3190/2/1/P01;jsessionid=42F67D42EFA1BDD2129056E975B21C29.c3

2.2(7) Smart interactive textiles

Smart and interactive textiles (SMITs) can sense electrical, thermal, chemical, magnetic or other stimuli in the environment and adapt or respond to them, using functionalities integrated into the textile's structure. They do not have a fixed set of characteristics, but are an active element that works with their own control and response mechanism.[54] SMITs are usually dependent on stimuli-responsive polymers and/or integration of sensor and communications technologies.

To date, the USA,particularly the military, but also NASA, has led the development of SMITs and applications for such areas as body armour, artificial muscles,[55] biochemical hazard protection, physiological status and location monitoring, and embedded communications and computing. Many of these technologies also have civilian and commercial applications.

In addition to defence, the medical industry has been a focus of SMIT research. Clothing that integrates conductive polymers has been designed for a number of applications, for instance in physiological monitoring. The MyHeart project, an EU Framework Programme 6 project, utilised integrated sensor technology to improve physical activity, nutrition, sleep and stress, as well as to monitor cardiac rhythms for early diagnosis and prevention of a range of heart problems including myocardial infarction, stroke and cardiac arrest.[56] Project Heart cycle aims to take this further to allow information to be shared both with the user and with health practitioners.[57]

The fashion industry is also a potential key market for SMITs. Philips has developed technology that integrates LED's into fabrics, while researchers have developed 'second skin' that acts as an emotional layer to deliver mood-responsive aromas and pheromones.[58] The design industry may make increasing use for SMITs in both clothing and other applications such as sensory wallpaper or clothes that interact with wallpaper or react depending on the input of a remote person.

2.2(8) Active packaging

Active packaging refers to a range of technologies that extends the function of packaging beyond passive protection. For example, packaging can be modified to allow selective gas exchange, or to change colour in response to changes in temperature. Integration of sensor technology and radiofrequency identification (RFID) into packaging also enables smart monitoring with implications for supply chain management and logistics. Key markets for active

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[54] http://www.electronics.ca/reports/materials/textiles.html
[55] http://www.newscientist.com/article/mg19125641.400-wrestling-the-musclebots.html
[56] http://www.hitech-projects.com/euprojects/myheart/
[57] http://www.heartcycle.eu/
[58] http://www.smartsecondskin.com/main/smartsecondskindress.htm

packaging include the food and pharmaceutical industries, in which a number of technologies have already been commercialised.

2.2(9) Metamaterials

Metamaterials are artificial materials that provide the ability to engineer material properties beyond those achieved from conventional materials and composites.[59] The material properties of relevance are those that define the manner in which materials influence a propagating wave. Light (electromagnetic waves including microwaves) and sound waves are the two most recognised types of wave but others include blast, seismic, matter and gravitational waves. Applications expected in five years' time include smaller, lighter and better performing antenna and other microwave components, but the possibility of the 'Harry Potter invisibility cloak'[60] remains distant. Metamaterials may also have applications in thermionics by enabling heat shields that convert heat energy directly to electricity.

2.2(10) Building and construction materials

Innovations in the construction industry could come from a range of initiatives, including new methodologies for determining the whole life-cycle carbon emissions of construction projects, improvements in supply chains and up-skilling of the workforce, as well as through technological innovation in a number of areas.

Fibrous composite materials offer a new wave of high performance applications, and their growing use is likely to be one of the major changes in this sector in the next decade. The reduced cost and high performance of glass and carbon composites, together with low maintenance requirements, are beginning to make them competitive. Recent examples include concrete embedded with carbon and polyvinyl-alcohol fibres. These composite concretes have improved compressive capacities and flexural strengths.[61]There is research currently looking at use of these materials, for example for foot and road bridges. Phase-change materials may offer advantages for thermal storage and air conditioning in buildings, and load shifting of power demands.[62]

Manufacturers are looking at ways to minimise emissions associated with materials. Concrete, a heavy user of energy in manufacture, is an important building material and companies such as

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[59]http://www.cmth.ph.ic.ac.uk/photonics/Newphotonics/pdf/sciam-pendry-4a.pdf
[60]http://www.nature.com/news/2009/090430/full/news.2009.417.html
[61]http://www.qub.ac.uk/research-centres/CenterforBuiltEnvironmentResearch/Research/ResearchOpportunities/PhDOpportunities/StructuralMaterials/
[62]http://www.jatit.org/volumes/research-papers/Vol4No6/6Vol4No6.pdf

Holcim and Novacem, are already developing low-CO_2 concrete.[63] New materials will play a role in meeting low-carbon targets.

Nanotechnology also plays an increasing role in construction materials. Two nanoparticles that stand out in their application in construction materials are titanium dioxide (TiO_2) and carbon nanotubes (see below). TiO_2 is used for its ability to break down dirt or pollution so that it can be washed off by rainwater on everything from concrete to glass, while carbon nanotubes can be used to strengthen and monitor concrete.

2.2(11) 3D printing and personal fabrication

Inkjet technology could give individuals the power to manufacture their own products. This idea has significant implications for high-tech customisation, for low-income countries' access to advanced technology, and for global economic competitiveness. It would vastly reduce the need to transport finished goods around the world, with substantial impact on the transport industry, including a reduction in its fuel use. Home-fabricated goods would have a small embedded carbon footprint, provided that the raw materials were produced locally. It could make a vast range of products from transplant organs to solar power-gathering materials simple and cheaper to produce.[64]

3D printing techniques have been utilised for a range of applications from product design and manufacturing to building biological tissues and large-scale housing production. Inkjet technology is ready for deployment in manufacturing processes and has already been used to deposit adhesives that bond chips to substrates in the production of memory chips. Scientists and engineers have experimented with using inkjet technology to print simple electronics and for 3D printing of simple structures and prototypes of products.

Progress in the area of 3D printing, or additive layer manufacturing as it is also known, during the past two years has been rapid. Home systems from Makerbot[65] and 3D System's Cubify[66] now retail for around £1000, and Solidoodle[67] has recently released a simpler product for about half this cost.£5000–10,000 now buys a very sophisticated product developed at the Eindhoven laboratories, which used to undertake research and development for Philips.[68] Meanwhile

[63] http://www.gizmag.com/novacem-calera-caron-capturing-concrete/14039/
[64] Horizon Scanning Centre Sigma Scan 2010 www.sigmascan.orgPaper No 436, 'From Ink-Jet Printing to Personal Fabrication'
[65] http://www.makerbot.com/
[66] http://cubify.com/
[67] www.solidoodle.com/
[68] http://fablabeindhonven.nl

companies such as D-Shape[69] offer to print diverse structures ranging from bus stops to harbour sections and altars.

Based on technology from the Materials Research Centre in Germany, the 3D-Bioplotter from EnvisionTEC[70] can be used in the field of tissue engineering to build scaffolds using a range of materials from soft hydrogels to hard ceramics and metals. Recently, researchers from University of Pennsylvania and the Massachusetts Institute of Technology used a 3D printer to build a sugar template to enable an artificial liver to be grown.[71]

A further application of the 3D printing approach developed recently is the 'solid freeform fabrication of food'. This is the term used to describe a process developed at the Cornell University Creative Machines Lab, which enables 'multimaterial food printing with complex internal structure suitable for conventional post-processing', in other words ready to cook.[72] The technology uses liquid or melted versions of conventionally produced ingredients. The next step is to create a range of 'food inks' made from hydrocolloids, which are substances that form gels with water, reducing food waste and the need for fertilisers and packaging.[73]

Decreasing the line width capability of 3D printers will allow for more complex printable structures. Printer head development and base material particle size are important steps while the control of colouring of manufactured objects may add a spectrum of capability and quality.

As 3D printing becomes more commonplace new legislation may be required to protect original objects and limit the scanning of an object for copying purposes.

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[69] http://d-shape.com/tecnologia.htm
[70] http://www.envisiontec.de/
[71] http://www.science-news.eu/research-news/cluster139989/
[72] http://creativemachines.cornell.edu/node/194
[73] http://www.ifst.org/documents/misc/HydrocolloidsSEPT09.pdf

2.3 Digital and networks

E-INFRASTRUCTURE (1–5)

2.3(1) Complexity

Complexity theory arose in the natural sciences as a response to the fact that the behaviour of many systems cannot be wholly explained by reference to their component parts, for example an ant colony appears vastly more complex than an ant. Complexity theory demonstrates that much of the order in such systems has arisen not from centralised control, nor from individual purpose, but from a natural, unplanned, self-organising behaviour that emerges as the components interact. Its areas of application range from risk assessment to the modelling of consumer behaviour.

The influence of complexity science is increasing in the areas of security, intelligence, nuclear proliferation research, and modelling and understanding terrorist networks. Complexity methods may be used to assess opportunities, risks, contingencies, and low-probability, high-impact ‘black swan’ events. Complexity principles in combination with scenario planning have been used to build on our understanding of leadership practice and decision-making processes to create new approaches in conflict resolution and resource management.

The issues posed by complexity are central to the future development of the natural and artificial worlds, and the possibility of blending them. In areas of technology such as robotics and nanotechnology, scientists are already building complex autonomous systems using the principles of emergence. By understanding how the human brain works, we may be able to engineer systems, such as prosthetics, controlled directly by the brain. To meet future demands it has been suggested that new information technology should be based on software that can create emergent intelligence or self-organise to react to unpredictable disturbances, as well as co-evolve over time alongside changes in their operating environment. Similarly, development of machine learning, for instance pattern recognition based on complex systems (for example, human cognition), would facilitate the development of novel ‘fuzzy’ searching software.

2.3(2) Supercomputing

Supercomputers have vast processing capability and are typically used to work on scientific and engineering applications, e.g. weather forecasting, aircraft and automotive design, pharmaceuticals, etc. Supercomputers are also employed in areas of research that generate huge datasets, such as particle physics and genetics. Over time, these capabilities will be available to the mass market, as new applications in media, gaming and ubiquitous computing require massive resources. The major computer and Internet companies are already recognising and exploiting the known opportunities. Realising these opportunities may depend on the skills to design software that can exploit the massive processing power.

On-demand supercomputing is only one of many names for the idea of high-performance computing programs linking supercomputer systems across broadband networks. This technology, currently under development in many research programs, includes grid computing, autonomic computing, adaptable computing, cluster computing and utility computing. The intention is to make computational power accessible in the same way that electricity is available from the electric grid – users simply plug into it without worrying about where the power is coming from or how it got there. In this method of computing, if more computing power is required, spare cycles on other computers are used. This means that the power of supercomputing is accessible without the huge costs of supercomputing, and that central processing unit cycles that would otherwise be wasted are put to good use.

There are competing visions of how this architecture is to be achieved. While the common view has been of a vast distribution of small resources, some now believe that it will be necessary to operate a more centralised grid infrastructure with, at its core, a network of massive resource nodes (peta-scale supercomputers).[74]

2.3(3) Cloud computing

Cloud computing is a general term for anything that involves delivering hosted services (for example business applications such as office suites) over the Internet. Cloud services have three distinct characteristics that differentiate them from traditional hosting: (1) they are sold on demand, typically by the minute or the hour; (2) they are elastic –users can have as much or as little of a service as they want at any given time; and (3) the service is fully managed by the provider – the consumer needs nothing but a personal computer and Internet access.

A cloud can be private or public. A public cloud sells services to anyone on the Internet – currently Amazon Web Services is the largest public cloud provider. A private cloud is a proprietary network or data centre that supplies hosted services to a limited number of clients.

Cloud services are broadly divided into three categories: infrastructure-as-a-service (IaaS), platform-as-a-service (PaaS) and software-as-a-service (SaaS). IaaS providers such as Amazon Web Services provide 'virtual servers' with unique IP addresses and blocks of storage on demand. Customers use the provider's application program interface (API) to start, stop, access and configure their virtual servers and storage. In this enterprise, cloud computing allows a

[74] Foresight Horizon Scanning Centre Sigma Scan 2008 www.sigmascan.org, paper 502, 'Supercomputing on Demand'

company to pay for only as much capacity as it needs and can bring more computing capacity online as required. Because this pay-for-what-you-use model resembles the way that electricity, fuel and water are consumed, it’s sometimes referred to as utility computing.

PaaS is defined as a set of software and product development tools hosted on the provider’s infrastructure. Developers create applications on the provider’s platform over the Internet. PaaS providers may use APIs, web portals or gateway software installed on the customer’s computer. Force.com[75], an outgrowth of Salesforce.com[76], and GoogleApps[77] are examples of PaaS. Currently, there are no standards for interoperability or data portability in the cloud. Some providers will not allow software created by their customers to be moved off the provider’s platform. Others have made the customer’s ability to move their data a selling point.

SaaS cloud models have the vendor supplying hardware and software and interacting with the user through a front-end portal. SaaS is a very broad market; services can be anything from web-based email to inventory control and database processing. Because the service provider hosts both the application and the data, the end user is free to use the service from anywhere.[78]

2.3(4) Next generation networks

The demand by customers for a convergence of capabilities (e.g. voice, data, video, etc.) delivered over networks and the Internet is increasing, as business practices and lifestyles change and consumer technology evolves. In order to meet this increased demand, the capability of service provision needs to be faster and of greater capacity. Connecting homes to the Internet over high-capacity fibreoptic cable, rather than copper wire, would provide an order-of-magnitude increase in download capacity, which may open up the potential for the delivery of new services and applications at increased speeds.

However, major telecoms companies argue that they do not yet see a business case for investing in fibre optic outside of new-build sites. They argue that there is limited evidence of demand for fibre optic and that most customers do not use all the bandwidth already available to them.Consumers are not prepared to pay significantly more for fibre optic than they now pay for existing broadband. In the past few years, the cost of broadband access has fallen, even as bandwidth has increased, due to strong competition.

[75] http://www.force.com/why-force.jsp
[76] http://www.salesforce.com/uk/
[77] http://www.google.com/intl/en_uk/enterprise/apps/business/
[78] http://searchcloudcomputing.techtarget.com/definition/cloud-computing

2.3(5) Intelligent sensor networks and ubiquitous computing

Sensors (light, motion, magnetism) are becoming increasingly small and increasingly connected, to each other and to either embedded or remote processors. Energy 'scavenged' from external sources (such as solar power, thermal energy, wind energy, salinity gradients and kinetic energy), can be captured and stored in small, autonomous devices made up of one or more sensors. Sensors will provide unprecedented access to information about the environment and potentially increase our ability to influence and control it, as well as improve detection and monitoring of changes.

We are beginning to see the miniaturisation of sensors, driven by the tools of nanotechnology, to the extent that sensors are already disappearing into all sorts of appliances and everyday objects, e.g. Gillette's insertion of RFID tags into razors. We are also gaining a better understanding of how physical, virtual and human networks behave. One result may be a decreasing distinction between physical and virtual environments, e.g. partial automation of the role of the vehicle driver. This has already happened in banking and online retailing, where complex systems include both physical and virtual components.

Tiny and cheap sensors could monitor the quality of drinking water, detect structural damage in buildings and vehicles, and sense and measure pollution in the environment. Machinery and consumer products could be monitored for the state of their components and materials, enabling them to report when repair or replacement is necessary. With progress in nanotechnology, a vast network of security sensors could provide continuous monitoring of critical infrastructures, such as buildings, bridges and pipelines, and detect chemical and biological agents from terrorist attacks.[79]

Mesh networks and low-energy wireless communication technologies will allow sensors to communicate their data, either as a seamless stream of unprocessed data, or, with improvements to software, to pre-process data, communicating only relevant or required information. Smart dust and speckled computing are two similar approaches to the development of intelligent networks of sensors. Both integrate sensing through MEMS (micro-electro-mechanical system) devices, or similar technologies, with processing units and communication technologies. While smart dust is essentially a fixed passive system once deployed, speckled computing combines the concept with that of swarm robotics to allow for intelligent reorganisation and reprogramming of the sensor network.

As sensor technologies become more prevalent, they will generate increasing amounts of data, with the associated problems of storage and processing. Advances in intelligent software and

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[79] Foresight Horizon Scanning Centre Sigma Scan 2008 www.sigmascan.org, paper 527, 'Nanosensors for Innovative Sensing Applications'

data analysis will facilitate adoption and use of sensor networks in a number of areas, including potential development of an electricity smart grid or traffic network management.

ANALYTICAL TOOLS (6–7)

2.3(6) Searching and decision-making

Advances in mathematical and statistical processing will underpin our ability to manipulate and make use of the greatly increased amount of data generated by advanced sensors and systems. This has the potential to transform decision-making and enhance cooperative ways of working. Searching and decision-making technologies are increasingly available for processing and analysing massive amounts of data. For instance, Wal-Mart handles more than 1 million customer transactions per hour, feeding databases estimated at 2.5 petabytes (2.5 million gigabytes). It uses this real-time information on what is selling, where and in what combinations to give more intelligent, and hence more cost-effective, stock management. Some companies use this data to help identify persistent trends and hidden links between factors, for example types of consumer purchase and the weather.[80] Tesco has utilised these data-mining techniques to get an in-depth insight into its customers and their behaviour, allowing it to offer discounts at strategic times and target its loyalty card rewards to individual preferences, as discerned from previous purchases rather than based on crude demographic criteria. This so-called relevance marketing increases loyalty and allows customers to be nudged towards new but relevant goods.[81] Since its introduction, this has helped Tesco to become the largest supermarket in the UK.

2.3(7) Simulation and modelling

Improved modelling of physical, environmental and human characteristics and behaviour, and their incorporation into simulations, offers the potential for innovations and improvements in many fields, including planning, decision-making, industrial processes, and training and education.

In science and engineering, modelling is the formulation of mathematical representations, or ‘models’, of real-world phenomena and processes. The models are then used as the basis for simulations to produce quantitative predictions.

[80] http://www.kylemurray.com/MDFP_JRCS2010.pdf
[81] http://www.technologyreview.com/news/428441/a-phone-that-knows-where-youre-going/

Modelling and simulation are widely used in many sectors of the UK, from financial services to health service provision. Models are used to support, and increasingly to replace, experimentation. Incorporating simulation into the design process can bring benefits, especially when the product development cycle is costly and lengthy, such as in the aerospace[82] and automotive industries. In the words of the US Integrated Manufacturing Technology Initiative: 'Modelling and simulation are emerging as key technologies to support manufacturing in the 21st century, and no other technology offers more potential than modelling and simulation for improving products, perfecting processes, reducing design-to-manufacturing cycle time, and reducing product realisation costs.'[83]

Modelling and simulation are also used to support product and process innovation and can help businesses respond to commercial and regulatory challenges. The discipline is well established in military training systems, and there is scope to extend its use into other areas of training, learning and education.

PROCESSORS, INTERFACES AND SENSORS (8–14)

2.3(8) New computing technologies

Silicon-based computing was a major influence on the 20th century and is likely to remain the predominant technology in the near future. However, advances in new computing technologies, including quantum, photonic and biologically inspired computing, offer new opportunities that may change the shape of computing over the next century.

New technologies are being developed to allow computer power to continue to grow despite any physical restrictions on silicon-based transistors.[84] Some approaches aim to improve the efficiency of existing computers, through efficiency improvements or through changes to how transistors operate, moving from high transistor power consumption to ensure reliability to a low-energy model designed to eliminate stochastic errors, while still other approaches represent fundamentally new methods of computing.

Quantum computing offers the opportunity dramatically alter the way that certain problems are calculated.[85] Quantum computing differs from traditional binary computing – which stores information using 'bits' that are limited to two states – by using 'qubits' (quantum bits) that can occupy multiple states simultaneously. Quantum computers can therefore theoretically perform calculations

[82]For example, the use of early computational fluid dynamics (CFD) tools to predict supercritical flows over wings was instrumental in enabling Airbus to establish itself as the main competitor to Boeing
[83]http://www.imti21.org/resources/docs/Modeling%20&%20Simulation.pdf
[84]http://www.iub.edu.pk/Documents/Mamoona../Limitation_of_Silicon_Based_Computation_and_Future_Prospects.pdf
[85] http://esciencenews.com/articles/2010/01/10/quantum.computer.calculates.exact.energy.molecular.hydrogen

significantly faster than any current classic computer. To date most efforts have operated with only a few qubits, when hundreds would be needed for a commercial system.

A US-based company, D-Wave, has built a functional quantum computer operating off 28 qubits with potential for scalability to 128 qubits within a couple of years.[86] Early reports state that Google has used this system for machine-learnt image recognition and searching, at speeds far greater than those available using existing Google data centres.[87] However, there is some debate about whether D-Wave is truly a quantum computer. Further advances in material technology are necessary to make quantum computing a commercial prospect, for instance to enable quantum computing at ambient temperatures.[88] There is much uncertainty about when (indeed, if) a full-scale quantum computer will be operational. Some estimates say not before 2035.

However, there is a real possibility that a quantum information processor (QIP) simulator will be available before then. Such a simulator would enable the development of quantum algorithms and applications. Whoever has access to such a device would have a significant advantage over those who do not. The bulk of the investment in QIP is from a mixture of governments and commerce so it is not possible to determine who will be the first to gain access to this technology (noting that there is no absolute assurance that it will be possible to build a larger scale QIP device at all, despite the huge worldwide monetary and intellectual investment in the activity).In terms of impact, if QIP is implementable, it will underpin the availability of massive computing power and an advanced cryptanalysis capability. Because of the nascent state of QIP, it is highly probable that further algorithmic and other advantages will be developed as our understanding develops. The opportunity and threat are symmetrical, in that whoever has initial access to QIP will have a portfolio of major, enduring advantages over those who do not.

DNA computing is also in its early stages. While it is unlikely that DNA computing will ever supersede current computers, it has already been applied to applications such as biosensing, including applications for the detection and treatment of cancer.[89] In DNA computing, computational problems are translated into DNA-like strings, which are mixed in a test tube. Their properties guide the way in which these strings combine into DNA strands, and this combination provides the solution to the problem. Because the process takes advantage of the ability of the many different components of DNA to try many different possibilities at once, DNA computers could offer highly parallel processing, using very little energy in the process. But DNA rapidly dissociates into double helixes. Although a DNA computation might be rapid, finding the desired answer represented by a particular strand in a test tube of thousands of other strands might require considerable lab work. While the most advanced DNA computer is almost unbeatable at noughts and crosses, it still requires human intervention to separate out the correct answer and is not reusable. The DNA approach is probably not well suited to

[86] http://www.newscientist.com/article/mg20126965.600-most-powerful-ever-quantum-chip-undergoing-tests.html
[87] http://www.newscientist.com/article/dn18272-google-demonstrates-quantum-computer-image-search.html
[88] www.azonano.com/news.asp?newsID=18296
[89] http://www.dna-computing.org/proceedings.html

general purpose computing such as word processing. If the process can be industrialised to become practical, a nanomolecular or DNA computer could be a cheap and low-energy massively parallel problem-solving machine. It would have a molecular nanomemory to permit fast associative searching, – the process of searching for information online in the context of related data to ensure its relevance. Further research in biocomputing is likely to be most active in the areas of the life sciences such as medicine, healthcare and agriculture.

Chemical computers, unlike DNA and quantum computers, are suitable for traditional computing applications, although likely to be less powerful than traditional computers. However, cheap and robust techniques include reaction–diffusion computing, in which waves carry information through a beaker of chemicals. Chemical computers could offer low-cost computing and allow development of amorphous robots.[90]

Neural computing is an alternative approach to chemical computing being undertaken by UK and European researchers funded by the EU Future and Emerging Technologies Programme.[91] Researchers are developing chemical-based cells that can function in a manner similar to that of the neuron, which aims to simulate or build artificial neural networks.

2.3(9) Photonics

The term photonics, or optoelectronics, covers a field that is analogous to electronics but in which the medium is light rather than electrical current and covers the generation, transmission, detection, manipulation and application of light and other radiant energy. Photonic technologies are already in widespread use (for example in communications systems, the Internet, computer processing and data storage), but further improvements in the performance, and falls in price, of many applications are expected.

Photonics has borrowed many techniques and processes from electronics, and the two fields have many shared applications. However, despite these areas of commonality, a truly integrated electronic-–photonic technology has not yet been realised, although we may be approaching the point at which such convergence is feasible.[92]Photonics technologies are already pervasive, with the US Optoelectronics Industry Development Association stating that 35% of all consumer devices have photonic components, whether in DVD players, or liquid crystal display (LCD) based devices including televisions.[93] Some of the uses and opportunities of photonics, such as the laser and the fibreoptic cable, are already well established and form critical parts of our

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90 ftp://ftp.cordis.europa.eu/pub/fp7/ict/docs/fet-proactive/chemit-02_en.pdf
91 http://cordis.europa.eu/fp7/ict/fet-proactive/docs/usef-48_en.pdf
92 Foresight Horizon Scanning Centre Sigma Scan 2010www.sigmascan.org, paper 422 'Information at Light Speed: Convergence of Electronics and Photonics'
93 http://www.berr.gov.uk/files/file39193.pdf

global data communications network, the Internet and numerous other systems on which we depend.

One area in which photonics has been suggested as having a large impact is in meeting energy consumption targets. Green photonics[94] currently comprises around 13% of the global market with estimates that this will surpass 50% by 2021, driven by a number of trends, including increased consumerdemand for electronics and a growing need for low-energy solutions for infrastructure, such as data servers, as system capacities and network traffic increases.[95]

2.3(10) Secure communication

The need to keep data secure is likely to spread to all areas of life. At the same time, we can expect to see increasing effort devoted to cracking codes. New technologies will bring entirely new principles for encryption of data. Among them, schemes based on quantum mechanics are perhaps the most striking. These offer the promise of secure communication by harnessing relatively simple concepts rather than relying on ever more complex or powerful computers and algorithms.The aspiration is to allow the cryptographic 'key', which enables the sender to encode and the receiver to decode the cipher text, to be exchanged between parties in absolute security. Quantum cryptography – or 'quantum key distribution' (QKD) as it should be called – exploits the fact that it is possible to create quantum systems that cannot be probed without becoming irreparably perturbed. In such systems any attempts by an eavesdropper to intercept the key unavoidably disturbs the system and alerts the sender and receiver.

Another approach to data security is steganography, the so-called digital watermark. These are electronic 'fingerprints' imprinted on data files. They are imperceptible to human users when, for example, they view digital images or listen to digital music, but can be detected by computer systems. Digital watermarks can be used to monitor and track the uses of such data files and to protect against counterfeiting and fraud. However, they raise a host of ethical and legal problems.

[94] http://cordis.europa.eu/fp7/ict/photonics/docs/studies/smart2010-0066-summaryreport-photonicstechnologiesandmarketsforalowcarboneconomy_en.pdf
[95] Michael Lebby presentation at to EPSRC BT Theme Day 2010

2.3(11) Biometrics

Biometrics are automated methods of recognising a person based on anatomical, physiological or behavioural characteristics. Among the features measured are face, fingerprints, hand geometry, handwriting, iris, retina, vein and voice. Biometric technologies are becoming the foundation of an extensive array of secure identification and personal verification solutions.

Biometric techniques can enable confidential financial transactions and can ensure the privacy of personal data. There is a need for biometrics in central, regional and local governments, in the military and in commercial applications. Enterprise-wide network security infrastructures, government identifications, secure electronic banking, investing and other financial transactions, retail sales, law enforcement, and health and social services are already benefiting from these technologies.[96]

While biometric solutions have been rolled out across UK airports, the UK government has halted plans to rollout biometric passports with stored fingerprint data.[97] However, there is likely to be increased future demand for government bodies and large firms to deploy high-tech security systems in a number of areas. For instance, biometric technology has been successfully utilised in the building industry: the UK Olympic Delivery Authority has utilised face and palm recognition to monitor construction workers and, during the 2012 London Olympic Games, to bolster security. Technology has also found uses in determining benefit and payroll fraud, for instance to eliminate ghost workers and double-dip claimants. Biometrics has also been heavily utilised in the casino industry.

Facial recognition technology and fingerprinting will become increasingly accurate as algorithms improve alongside continued investment in research. However, iris recognition has emerged as a highly accurate technique, with recent research suggesting that the technique remains highly accurate when using low-resolution images.

Recognition algorithms that can utilise existing scanning technology are key to the success of any biometric technology, though advances in imaging will allow increasingly detailed measurement to be made. However, widespread adoption of technologies will be dependent on the development of industry standards and compatible hardware and applications that allow recorded data to be shared.[98]

A significant barrier for adoption of biometric techniques is public acceptance of the technology. Concerns over privacy and data protection are highly pertinent, and parallels can be drawn with the

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[96] http://www.biosig-id.com/wp-content/uploads/2011/08/Biometric-Signature-ID-highlighted-in-Biometrics-Technology-Today.pdf
[97] http://www.ips.gov.uk/cps/rde/xchg/ips_live/hs.xsl/1691.htm
[98] http://www.sciencedaily.com/releases/2009/11/091104101628.htm

debates surrounding the UK national DNA database[99], and early concerns over the acceptability of DNA fingerprinting technologies used as court evidence[100].A further concern surrounds the ability to reverse engineer a person's identity by gaining knowledge of their individual biometric profiles.

Novel techniques for biometrics may arise from advances in DNA and related research. The reduced cost of DNA sequencing combined with novel sensor technologies may facilitate the development of biometric technologies and standards around a person's genome.

2.3(12) Surveillance

A number of technologies will play an increasing role in the future of surveillance. These include video cameras and closed-circuit television (CCTV) systems, satellite surveillance systems, audio receivers and recorders, radar traffic enforcement devices, motion detectors, heartbeat detectors, 'radar flashlights' to detect breathing and other vital signs, devices to 'see' through walls and into enclosed spaces to locate and track concealed persons, and night vision and thermal imaging devices that detect infrared radiation or heat. Analysis of live data streams by 'artificial intelligence' agents will allow more proactive surveillance, potentially alerting operators to crowd control problems or identifying persons of interest. These features will be augmented by facial recognition technologies, which will link up with national biometric databases. Improved large-scale wireless networks could enable a big increase in the range of locations for CCTV cameras and sensors, eliminating previous blackspots. Combined with the emerging field of 'micro-drones' (small unmanned aerial vehicles), it could be possible to keep all areas and spaces under surveillance, a possibility that is likely to raise major privacy concerns.

2.3(13) Service and swarm robotics

Although the number of robots operating in the UK is growing steadily, the tasks they are doing remain predominantly those previously associated with skilled manual labour. Few robots, outside research laboratories,can learn or make decisions or possess other attributes of 'intelligence', despite having a humanoid appearance in some cases. However, the past decade has seen increased utilisation of robotics in agile manufacturing, logistics, medicine, healthcare, and commercial and consumer market segments.

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[99] http://www.parliament.uk/documents/post/postpn258.pdf
[100] http://heinonlinebackup.com/hol-cgi-bin/get_pdf.cgi?handle=hein.journals/cdozo13&section=21

Robotics have historically been utilised in arenas such as the manufacturing industry to reduce costs and increase performance in tasks that are unsuitable for humans or that require high levels of accuracy or reproducibility, including automation of car assembly lines**.**

The principal markets for service robotics include defence, healthcare, manufacturing, transport, energy, entertainment and education. Already there are established market positions experiencing significant growth in industrial inspection, agricultural and underwater surveying and surveillance robots.

Using swarms of individually ‘stupid’ robots to complete extensive or complex tasks will become increasingly commonplace. For example, the Ocean Systems Lab at Heriot-Watt University is developing ‘coralbots’ to assist with coral reef restoration.[101] Markets for care robots and entertainment robots are also likely to be important.

Autonomous vehicles, either uninhabited or with passengers, were made a reality with Google’s car and ‘intelligent’ uninhabited air vehicles. However, public perception may prove to be the barrier to widespread application, rather than safety.

2.3(14) Bioinspired sensors

The diverse range of sensors found in nature may be categorised as mechanical (flow, vibration, force, angular rate, tactile and acoustic), electromagnetic (visual and infrared radiation, electric field and magnetic field) and chemical (gustation and olfaction). Emerging understanding of their working, together with the development of new materials and fabrication processes, increasingly allows the realisation of devices that exploit the principles underlying biological sensors without necessarily copying exactly the natural structures. Thus, bioinspired sensors should be carefully distinguished from biosensors.

The emergence of bioinspired sensing as a separate discipline has been reflected in the growth in the number of journals and conferences wholly or largely focused on bioinspired sensing.[102]

Much current bioinspired research has arisen from the vision and flight systems of insects and is related to autonomous vehicle research. MEMS-fabricated arrays of artificial hairs inspired by the cerci of crickets have demonstrated sensitive, directionally discriminating airflow sensors.[103] An insect eye-based, ultra-wide, field-of-view optical sensing system accurately detect and image distant targets has been developed, and image-processing techniques, inspired by the

[101] http://knowledgetransfer.hw.ac.uk/tag/coralbot
[102] http://www.mdpi.com/journal/sensors/special_issues/biosensor_syst
[103] http://biomimetic.pbworks.com/f/Cricket+Inspired+Flow-Sensor+ArraysKrijnen.pdf

relatively low neuron numbers used in insect vision systems, are being developed. The microscopic eye of *Xenospeckii* was the inspiration for BAE's revolutionary new imaging system, 'Bug Eye', for missile-tracking applications.[104] Polarimetric and multispectral imaging systems have been developed for the detection of difficult targets and are bioinspired in the sense that they mimic the imaging systems of insects and mantis shrimp. Other notable achievements include biomimetic strain sensors inspired by the campaniformsensilla of insects developed for space applications.[105]

Many organisations now have established research programmes pursuing bioinspired sensors, and dedicated research laboratories are beginning to be established.

2.4 Energy and low-carbon technologies

INFRASTRUCTURE (1–3)

2.4(1) Smart grids

A recent study by the Energy Research Partnership draws attention to the challenge of ensuring that power supplies are maintained when intermittent supplies are not available (in the case of wind energy, for example, when the wind is not blowing). To some extent this can be mitigated by a 'sensible generating mix'. Otherwise, options such as energy and thermal storage technologies and interconnections with other countries' grid systems can be explored, but further work is needed to demonstrate their potential scale and performance.[106]

New energy storage systems will play a role in providing back-up, particularly those that can decouple power output and storage capacity. Work on flow battery technology is taking place at Imperial College London and at Southampton and Manchester Universities, while sodium ion batteries are being researched at St Andrews and Cambridge. Another approach, offered by Highview Power Storage, uses liquid nitrogen to store energy, which is released by bringing the nitrogen back to ambient temperature.

Although significant progress has been made in the development of smart meters, it is increasingly well understood that the major benefit from a smart grid system resides in the ability

[104] http://www.baesystemseducationprogramme.com/what-is-engineering/bug-eye.php
[105] http://biomimetic.pbworks.com/f/Biomimetics+of+Campaniform+Sensilla+MeasuringVincent.pdf
[106] http://www.energyresearchpartnership.org.uk/tiki-index.php?page=Flexibility+Options

to implement automatic control of systems and appliances, which will require the agreement of energy consumers.

2.4(2) Microgeneration

Microgeneration is the production of heat and/or electricity, usually from a low-carbon source, on a small scale. The potential market may be millions of homes and businesses, although modifications to the nation's power transmission infrastructure are likely to be necessary. Microgeneration technologies include solar photovoltaics, micro-wind turbines, solar thermal water heating, fuel cells, micro-combined heat and power, heat pumps, micro-hydro power schemes and biomass boilers.

The widespread adoption of localised energy generation may require modifications to the nation's power transmission infrastructure to accommodate local generation surpluses. In the next 20 years, new scientific and engineering knowledge may reshape this infrastructure by shifting key points of power generation to very small portable units. Initially, this trend will be marked by miniaturisation of existing technologies such as fuel cells, gas turbines and photovoltaics. Over time, progress in materials and micro/-/nanotechnology may permit power generation and storage via a wider range of techniques than is currently possible.[107]

There is also potential for microgeneration techniques to power a network of remote sensors. This already occurs with weather-monitoring systems, but true miniaturisation of energy-generating technologies would allow a much wider range of applications in sensors.

2.4(3) Advanced batteries

Advanced battery technologies aim to develop modern alternatives to the traditional lead-acid battery, such as lithium-ion.[108] Advanced batteries could replace fossil fuels in transport, cutting CO_2 emissions, if electricity from low-carbon sources could be used to charge the batteries, and if and when they offer equivalent, or better, energy/power density than fossil fuels. The technology could also create local storage for electricity created by microgeneration and a way of balancing the contribution to the grid of intermittent generation from renewables, as well as enabling the development of new portable technologies.

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[107] Foresight Horizon Scanning Centre Sigma Scan 2010 www.sigmascan.org, paper 453, 'Decentralisation of electrical power?'
[108] http://www.technologyreview.com/news/419591/a-guide-to-recent-battery-advances/

CARS AND BEYOND (4–6)

2.4(4) Intelligent low-carbon road vehicles

It will be necessary to both change consumer behaviour and develop low-carbon transport solutions to meet UK 2020 carbon emission targets. A range of technologies is likely to be available to improve, or even replace, the internal combustion engine, and information technologies and other mechanisms for changing human behaviour are likely to combine with these to reduce overall environmental impact while maintaining individuals' access to personal and public transport.

2.4(5) Fuel cells

Fuel cells convert either hydrogen or a wide range of hydrocarbons and alcohols into electricity and, in some cases, heat, at high efficiency and with low emissions compared with other technologies. They are being developed for a wide range of applications such as replacing batteries in consumer goods or the internal combustion engine in road vehicles and locally generating power for industry.

The fuel choice depends on the application and the type of fuel cell. Fuels include hydrogen, methanol, ethanol, natural gas, liquefied petroleum gas, diesel and gasoline. Fuel cell R&D is a multidisciplinary field, encompassing material science and engineering, catalysis, electrochemistry, thermal fluids, system design, integration and control, and power conversion.[109]Traditionally, three main fuel cell types have been the focus of UK research: alkaline, polymer and solid oxide, with the polymer and solidoxide fuel cells receiving most attention. More recently, research has spread to novel fuel cell technologies including direct methanol fuel cells, which can be refilled easily with methanol.[110]

The hydrogen fuel cell vehicle market, although less mature than electric vehicles (itself developing), could deliver low-carbon vehicles with greater efficiency and range as fuel cells theoretically have a high energy density and greater efficiency. However, current development is hindered by high capital costs and the lack of a hydrogen infrastructure. Advances in fuel cell technology and scalable manufacturing could drive costs down to a competitive level by 2025.

There are only a handful of global companies that currently develop fuel cells for applications in buildings, but solid oxide fuel cell systems may offer a solution. The cost remains prohibitive for general uptake but is expected to fall in the long term. The ability of such technologies to utilise fossil fuels, as well as low-carbon energy sources, such as hydrogen or biogas, could facilitate

[109] http://ukerc.rl.ac.uk/Landscapes/Fuel_Cells.pdf
[110] http://media.wiley.com/product_data/excerpt/75/35273237/3527323775.pdf

the development of energy infrastructure as grids move towards renewables and microgeneration and, potentially, towards a hydrogen economy.

Fuel cell technology has improved since 2010 and made major strides commercially, notably in Japan where in the past 15 months 30,000 domestic micro-combined heat and power systems have been purchased at an installed price of approximately £15,000 per unit after government subsidy.[111] The Ene-Farm system is a gas-derived hydrogen fuel cell offering high energy efficiency, at 46.5%, by generating electricity and using the residual heat to boil water. The system is smart and learns the usage patterns of the household, providing energy and hot water on demand.

Horizon[112] of Singapore commercialises mobile hydrogen fuel cell systems that can power cars and even small aeroplanes. The technology is being brought to the UK through a partnership with Arcola Energy supported by the Technology Strategy Board.[113]

Commercial hydrogen fuel cell vehicles from Toyota and Daimler Chrysler are due to be available from 2015, with other manufacturers in Japan, Germany, China and the USA also developing models for release between 2015 and 2018. To evaluate how the UK should support this activity, a group called UKH2Mobility was launched in January 2012,[114] bringing together three UK government departments and participants from the utility, gas, infrastructure and car-manufacturing sectors.

2.4(6) Hydrogen

Hydrogen is potentially the most important alternative to hydrocarbon fuels in future low-carbon energy systems. The term ‘hydrogen energy’ covers all aspects of the use of hydrogen in energy systems, from the production of hydrogen from primary or secondary fuels through the storage and distribution of hydrogen to the enduse of hydrogen (usually but not exclusively in fuel cells) in stationary, transport and portable applications.

Hydrogen is an energy carrier, complementary to electricity and is carbon free at the point of use. It can be produced in many ways, including steam reforming of natural gas, biomass gasification and electrolysis of water. The overall carbon emissions from the fuel chain will depend on the primary fuel used and any carbon capture and storage processes associated with the fuel.

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[111] http://www.fuelcelltoday.com/media/1597029/29-02-12_ene-farm.pdf
[112] http://www.horizonfuelcell.com/
[113] http://www.renewableenergyfocus.com/view/24267/arcola-energy-horizon-to-launch-global-fuel-cell-product-integration-platform/
[114] http://www.bis.gov.uk/news/topstories/2012/Jan/hydrogen-fuels-lower-emissions

A hydrogen energy system, at any scale, would need to be justified in terms of its economic advantage or significant environmental benefit. In both the markets for stationary heat/power and transport, hydrogen and fuel cells will have to compete with incumbent fuel technologies (natural gas and petroleum) that already have fully developed infrastructures. Early support through demonstration and, at a later date, suitable incentives, would be necessary to move towards a position in which hydrogen played a major role within a low-carbon economy. A key research challenge is to assess the 'whole system' viability of hydrogen's role within a low-carbon economy and its socioeconomic and environmental costs and benefits: much data have now been published, and the different modelling approaches now give reasonable agreement. At the same time, there remain significant technical challenges to make individual components of the hydrogen economy work effectively.

The hydrogen verses electricity debate has moved on: even proponents of hydrogen now talk about 'hydrogen *in* the economy' rather than '*the* hydrogen economy'.

Although many challenges remain, progress is being made and more is expected on hydrogen storage: from load-following electrolysers buffering energy generated by wind turbines to chemical storage in the form of metal hydrides[115] and physical storage in metal organic frameworks.[116]

Hydrogen can be produced using excess energy from nuclear or intermittent sources such as wind turbines. An alternative is to draw off a supply of hydrogen from a pre-combustion carbon capture system (CCS). The advantage of this approach is that the CCS plant can be 'switched' when extra grid electricity is needed, for example in calm conditions when wind turbines are not working, so that the hydrogen generates electricity in a closed cycle gas turbine. The two approaches, combined with new storage options for hydrogen, offer a useful complementary approach to balancing the electricity grid compared with batteries, pumped hydro (in the UK and abroad) and demand-side grid management.

[115] http://www1.eere.energy.gov/hydrogenandfuelcells/storage/metal_hydrides.html
[116] http://www.nature.com/nchem/journal/v1/n6/full/nchem.333.html

RESOURCE EFFICIENCY (7–8)

2.4(7) Recycling

Increasing recycling of all forms of waste could save energy and natural resources and would reduce our dependence on increasingly expensive raw materials and increasingly scarce landfill sites.[117] There is a complex relationship, partly driven at EU level, between recycling targets mandated by legislation and recycling that generates revenue.

There is significant market potential in recycling but barriers remain to market development. There is potential to significantly improve efficiency and capacity for recycling by introducing more effective processes, such as closed loop production, and applying new technologies and innovation. This would save costs, energy and natural resources and, as a result, reduce our dependence on increasingly expensive raw materials.

Technologies already exist for identifying, separating and recovering high-value components from waste streams: industrial-scale sorting/separation of comingled material is being achieved at mechanical biological treatment, mechanical heat treatment and material recycling facilities to produce economical recyclate streams. This can avoid costs of multiple kerbside collections. However, cost issues remain as many of the recyclate streams have a market value far below their costs of recovery.[118]

2.4(8) Carbon capture and storage

Carbon capture and storage (CCS) technologies are intended to prevent CO_2, produced by burning fossil fuels to generate electricity, being released as a greenhouse gas into the atmosphere.[119] CCS technologies may allow fossil fuels to remain major components of power generation despite the demand for low-carbon electricity generation. Rather than a single technology, CCS covers a series of technologies enabling the capture of $CO_2$from fossil fuels and transport of liquefied CO_2 and its geological storage.

Carbon capture removes CO_2 from fossil fuels either before or after combustion. Capture is the most expensive stage of the CCS chain, accounting for about 70% of the cost. Substantial research efforts are underway to reduce its energy penalty and costs. Of three possible capture methods, the most

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[117]Foresight Horizon Scanning Centre Sigma Scan 2010 www.sigmascan.org, paper 145, 'Talking rubbish: the struggle to conquer the growing waste mountain'Rubbish: The Struggle to Conquer the Growing Waste Mountain'
[118]http://www.resourcefutures.co.uk/content/quality-recyclate-outputs
[119]http://www.bis.gov.uk/go-science/climatescience

mature, post-combustion capture, or ‘scrubbing’, is routinely used for flue gas separation in the petrochemicals industry and urea manufacture. Post-combustion capture is of interest to the UK as the technologies can be retrofitted to existing power plants.

Pre-combustion capture involves the removal of carbon from fuels before combustion. When integrated with fuel gasification and large-scale hydrogen production on new plants, it could be a low-cost method of carbon separation. Pre-combustion separation is mature in petrochemical plants, and there are more examples of its deployment at the power generation scale than there are of post-combustion approaches.[120]

Another main technology under development in Europe is integrated gasification combined cycle (IGCC). The technique is based around the gasification of coal to produce syngas, consisting predominantly of CO and H_2O, and is described further below. A project has been developed for IGCC with CCS in the UK at Hatfield in Yorkshire.

Oxyfuel capture is a separate technology that involves burning fossil fuels in pure oxygen rather than air. Heat from the burner generates steam, which is fed into a turbine to generate electricity as usual, while the waste gas exits the boiler and passes through several cleaning processes to remove small particles and sulphur to produce a gas that is almost entirely CO_2. The CO_2 is then condensed to a liquid phase for transport to storage. Oxyfuel burners could be retrofitted to enable efficient separation of concentrated CO_2 combustion gases. However, cheaper separation of oxygen from air will be required.[121]

Carbon storage is the long-term storage of carbon or CO_2 underground in, for example, depleted oil and gas reservoirs, coal seams or saline aquifers. Storage sites are geographically dispersed around the globe. The North Sea is potentially an ideal carbon storage site. Some observers believe that it may provide an enormous market over many decades. However, there are some concerns as to the long- and short-term safety of carbon storage, as well as issues around liability. Although there is an evidence base from natural analogues and full-scale trials showing that geological storage will be effective, there is a need to gain experience in the selection and operation of sites to build confidence. There will need to be significant infrastructure to carry and store carbon.

CCS plants cost more than existing coal and gas plants, and are less efficient. Economic viability depends on the extent to which demonstration plants can help reduce costs and whether the price of carbon offsets the loss of efficiency and increased costs associated with adopting CCS technology.

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[120]Foresight Horizon Scanning Centre Sigma Scan 2008 www.sigmascan.org, paper 440, ‘Clean Coal Energy Generation Using Gasification Techniques’ and paper 459, ‘Synfuels as a Real Alternative to Oil’
[121]http://ukerc.rl.ac.uk/Landscapes/CO2CS.pdf

ENERGY TECHNOLOGIES (9–14)

2.4(9) Nuclear fission

Nuclear fission provides a reliable, large-scale, low-carbon source of electricity. Over the entire life-cycle of nuclear power production (including uranium mining, decommissioning and waste disposal) CO_2 and other emissions are low, comparable to wind power. However, there is a range of long-standing concerns held by potential utility investors, government and/or the public, including cost, safety, regulation, proliferation and waste disposal, which may continue to slow uptake in the UK.

A range of new and enhanced nuclear technologies continues to be developed, although the future needs for reactor and fuel development is highly dependent on which generation of reactor is being considered. In the case of the current operations of Generation II plants, the emphasis will be on lifetime extensions, primarily driven by material performance, e.g. reactor pressure vessel performance, and by the balance between cost of production of safety cases and additional revenue from extended operation.

Most new-build nuclear plants are Generation III technologies, with a standardised design to reduce cost and expedite licensing and construction times, increase availability and operating life, increase burn-up to reduce fuel use and waste, and increase safety, notably with passive/inherent safety features. Some of the reactor designs currently being considered for new builds can produce over 1600 megawatts of electricity.

There are four main types of Generation III reactors: light-water reactors – including advanced boiling water reactors and advanced pressurised water reactors; heavy-water reactors; high-temperature gas-cooled reactors; and fast neutron reactors. Generation IV technologies are now under development. The Generation IV International Forum (GIF),[122] an international taskforce of 13 countries, is pursuing six clean technologies selected on cost, safety and sustainability: gas-cooled fast reactors; lead-cooled fast reactors; molten salt reactors; sodium-cooled fast reactors; supercritical water-cooled reactors; and very-high-temperature gas reactors. Most of these technologies use a closed-fuel cycle to minimise waste. UK organisations are able to participate in GIF both directly, as part of international consortia, and through the European Atomic Energy Community (Euratom).[123] UK research councils support areas of UK research activity relevant to the development of Generation IV reactors.

Such reactors will operate in new ways that can exploit the full energy potential of uranium, thus greatly extending resource availability – by factors of up to 100 over current technologies. The

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[122] http://www.gen-4.org/
[123] http://www.euratom.org/

new reactors are planned to improve safety still further and produce less radioactive waste. They will also reduce the risks of nuclear weapons proliferation.

High-temperature reactors will also have the ability to co-generate electricity and heat for industrial purposes, such as process heat for the oil, chemical and metal industries, for example, and for hydrogen production and seawater desalination.

There is a big challenge in the management of spent fuel inventories, given that a significant amount of spent fuel from the Generation II plants will require long-term storage or disposal or recycling if this is an option to be considered in the future. This will also be the case for fuel for Generation III plants. There are challenges relating to how to best utilise the current UK stocks of reprocessed uranium and plutonium, which could be recycled for use in fresh fuel or stored for a future option or placed in a repository along with existing stocks of intermediate- and high-level waste.

There is a near-term opportunity (i.e. over the next decade) to develop innovative technology that provides a step change in management of the post-operational legacy of nuclear operations including the retrieval and clean up of legacy wastes and contaminated land.

Interest in small nuclear reactors, from pre-fuelled 10 megawatt systems to 300 megawatt modular reactors, is growing for several reasons: notably the lower costs of building and decommissioning; lower complexity (linked to cost and safety); and greater flexibility. Many of the cost savings come from the fact that such systems can be made and licensed in a factory, rather than waiting four years after construction for tests and certification.

The US Department of Energy is interested in the 100–300 megawatt range,[124] which can either be used on their own to meet energy needs in isolated regions, or can be 'networked' into multi-reactor systems that provide both flexible scale and redundancy in the event of one reactor needing to be taken offline.[125]

2.4(10) Nuclear fusion

Nuclear fusion is the process that heats the sun. The goal of fusion research is to establish it as a viable option for meeting the world's energy needs. The particular strengths of fusion are the enormous fuel resources, capable of providing thousands of years of energy supply, its intrinsic safety, due to very low energy and fuel inside the power plant at any time, and the extremely low levels of atmospheric emissions, particularly of carbon dioxide.

[124] http://www.ne.doe.gov/
[125] http://www.scientificamerican.com/article.cfm?id=small-reactors-bid-to-revive-nuclear-power

Fusion made enormous progress when the current generation of devices, such as JET (Joint European Torus), were built, following the oil crises in the 1970s. This led to the production of 16 megawatts of fusion power, thousands of times higher than was possible before.

The first generation of fusion reactors will almost certainly use the deuterium–tritium reaction. Concerns remain over the production and use of tritium in fusion reactors. Despite its relatively short half-life, tritium is both biologically and environmentally toxic. In addition, as with uranium, there is a proliferation issue. Producing energy from the fusion of deuterium with itself is technically possible but more difficult.

The main research challenges have been: achieving the conditions needed for fusion; developing materials suitable for a fusion environment; and addressing the technological challenges associated with large-scale fusion power production. The first is largely solved, and the emphasis globally is shifting towards materials and technology issues.[126]

There are two main experimental approaches to fusion power: magnetic confinement and inertial confinement. The most common magnetic confinement technologies are the tokamak (e.g. the International Thermonuclear Experimental Reactor, ITER, and JET), stellerators (e.g. the large helical device) and reversed field pinch technologies. Inertial confinement involves the use of laser or ion beams, with the majority of research focused on lasers (NIF and HiPER).[127]Tokamaks are proving the most stable technology.

Many countries conduct fusion research in a highly coordinated effort. The UK's work is an integrated part of the EU's effort, which, in turn, is increasingly coordinated with work on other continents. These collaborations are most clearly seen in the collaborative EU venture, JET, the world's biggest fusion device to date, located in the UK, and ITER, the new device being built in France. ITER is designed to produce 500 megawatts of fusion power and provide the evidence to define the parameters for a viable fusion power plant.

Low-energy nuclear reactions, 'so-called cold fusion', remains a potential wild card: the US Department of Energy (2005) assessment panel left the debate still open,[128], while apparently successful development work continues in the US Navy.[129]

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[126] http://ukerc.rl.ac.uk/Landscapes/Fusion.pdf
[127] https://fec2012.iaea.org/conferenceDisplay.py/abstractBook?confId=10
[128] http://www.scientificamerican.com/article.cfm?id=back-to-square-one
[129] http://www.springerlink.com/content/75p4572645025112/

2.4(11) Bioenergy

Bioenergy encompasses all energy derived from biological organisms. The use of bioenergy is not a new phenomenon, for instance the burning of plant material utilises bioenergy. However, a renewed focus on realising the potential of bioenergy has emerged alongside arguments for reducing carbon emissions and developing sustainable sources of energy. Bioenergy is a flexible resource that can be converted for a range of applications including energy production, transport, heat and power. However, bioenergy resources are limited and there are sustainability concerns that need to be managed.

Although some concern remains about the future availability and price of biomass feedstock and the impact of biomass use on sectors such as agriculture and the furniture industry, bioenergy is seen as a significant source of low-carbon energy.[130] Improving the productivity of bioenergy crops may help relieve that tension and is the focus of the Biotechnology and Biological Sciences Research Council's (BBSRC's) Sustainable Bioenergy Centre, as well asthe Engineering and Physical Sciences Research Council's (EPSRC's) SUPERGEN Bioenergy Hub. The focus in bioenergy to 2030 is on waste-to-energy systems and combined heat and power (CHP), use of biomass to provide low-carbon heat for high-temperature industrial processes, and the replacement of capacity from coal power stations soon to be taken out of service.

Beyond 2030, there may continue to be a role for bioenergy in helping to meet the 2050 emissions targets, if CCS technology can be used in conjunction with bioenergy production. The UK Energy Technologies Institute is exploring the feasibility of this option in its Biomass to Power with Carbon Capture Storage project, started in 2011.[131]The project explores, at an engineering level, the cost-effectiveness, technology challenges, technology developments and likely timescales for implementation required for biomass to power combined with CCS.

2.4(12) Solar energy

No single technology stands out in its potential to deliver future solar energy innovation, but it is clear that more research emphasis needs to be placed on manufacturing processes. Artificial photosynthesis is an unknown quantity, but fuels produced using solar energy would transform our energy options in the future and there is considerable research strength in the UK.[132] One opportunity is to capitalise on opportunities presented by plastic photovoltaic (PV) materials. In general materials research aimed at improved PV devices must constantly take efficient manufacturing into account. Although most of the research challenge lies in the design and

[130] UK Bioenergy Strategy (2012) http://www.decc.gov.uk/assets/decc/11/meeting-energy-demand/bio-energy/5142-bioenergy-strategy-.pdf
[131] http://www.eti.co.uk/technology_programmes/bio_energy/
[132] http://www.rsc.org/ScienceAndTechnology/Policy/Documents/solar-fuels.asp

manufacture of PV devices, systems are presently let down by underperforming components such as inverters.[133]

2.4(13) Marine and tidal power

Marine energy involves generating electricity from waves, tides, thermal gradient and salinity gradient (osmotic power). A wide range of marine energy technologies is under development both internationally and within the UK. It is estimated that there are about 150 wave and tidal energy devices in development around the world, with no clear winners at present. Wave and tidal energy is now approaching the commercial-scale prototyping stage and has the potential to establish a new engineering and manufacturing sector in the UK.

Wave energy includes a range of technologies under development to extract energy from waves. These include attenuators, point absorbers, oscillating wave surge convertors, oscillating water columns, overtopping devices and submerged pressure differential technologies. So far there is no convergence on an agreed design or concept in the sector, with different technologies suited to either shoreline or deep waters. The coasts of western Scotland, south-west Wales and Cornwall are likely to be the preferred sites for developers.

Tidal stream technologies operate on a similar principle to wind turbines, but utilise the underwater currents of the tides. The challenge for tidal energy technology is to prove that it can generate electricity reliably and economically. However, as UK waters exhibit some of the strongest tidal zones in the world, tidal stream technology may be of significant benefit to meeting UK renewable targets. The Pentland Firth, Pembroke and Anglesey are among the most promising sites.

Tidal range technologies make use of the height difference between high and low tides to capture and store water at high tide for release at low tide. The potential energy stored is used to generate electricity as it flows through turbines. Two key technologies are the tidal barrage and tidal lagoon. Tidal barrages span the entire width of a channel: as the tide comes in it is allowed to flow through sluice gates, which then close at high tide. Once the tide falls, water is allowed to flow out through turbines. Tidal lagoons differ in that they are used to impound only part of a channel. The Severn Estuary is by far the most important of five major UK sites where tidal stream and tidal range technologies could be deployed, with the potential to generate up to 30% of the 52 terawatt hours of tidal range energy generation possible in the UK each year.[134]

Ocean thermal energy conversion (OTEC) operates using a different principle from wave and tidal power, being dependent on the natural temperature differential between warm tropical surface water

[133] http://ukerc.rl.ac.uk/Landscapes/Solar.pdf
[134] http://assets.wwf.org.uk/downloads/positive_energy_glgh_technical_report.pdf

and cold deep-sea water from depths of around 1000 metres. A temperature difference of 20 degrees centigrade or higher is required for OTEC to be viable. This means that potential for OTEC deployment does not exist in UK waters; however, there is opportunity for large installations that can graze on high seas outside exclusive economic zones.

Osmotic power is another potential technology that may be of benefit to the UK. Here, sea water and fresh water are pumped onto different sides of a semi-permeable membrane generating osmotic potential and a resultant pressure gradient, which can be used to drive a turbine. The world's first osmotic power plant has been established in Norway, although the key issue will be whether the technology can be scaledup.

2.4(14) Wind energy

Wind energy is expanding rapidly in the UK, with offshore wind offering the greatest potential. By capitalising on existing offshore engineering expertise, there is opportunity for considerable manufacturing activity. Wind technologies are relatively advanced, although nascent technologies will continue to improve with technological advances in design, manufacturing and materials. There are three key markets for wind energy: offshore, onshore and small wind, each having distinct opportunities and characteristics but with broadly similar technology.[135]

Onshore wind is the most established market in the UK, with 264 wind farms operating in the UK at a peak capacity of over 3.5 gigawatts.[136] Most onshore wind turbines, as with offshore wind turbines, are 'windmill-like' horizontal axis wind turbines. A variety of designs exist, with the majority of the UK build based on three-blade designs suitable for stronger winds.

Offshore wind is considered to be a key future market in the UK, and the country is already the global leader for operating offshore wind with over 1 gigawatts of installed capacity. On top of this, projects with a generating potential of over 6 gigawatts are in the pipeline, being either at various stages of construction or awaiting consenting or financing decisions.

Small wind turbines have been used for battery charging of remote power supplies, where a grid connection is not available or would be prohibitively expensive. Small wind turbines with mains inverter interfaces are now being developed for domestic applications. There are over 600,000 small wind systems in the UK, with a capacity of 1.3 gigawatts. Estimates suggest that 9 gigawatts of energy could be generated through small wind turbines by 2040.

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[135] http://www.decc.gov.uk/assets/decc/what%20we%20do/a%20low%20carbon%20uk/2050/216-2050-pathways-analysis-report.pdf
[136] http://www.bwea.com/statistics/

3. New themes

Three emerging themes have been identified which may be important: the *energy transition* to smart grids and an energy mix that balances intermittency from growing renewable sources and the accessibility of gas; *on demand*, where new printing technologies that are revolutionising traditional manufacturing processes and expanding the potential of regenerative medicine; and *human-centred design* where connectedness and sensors that are growing in ubiquity and generating data to be processed by ever-more computing power, but there are questions over whether challenging the designers of algorithms can fully harness the potential.

3.1 Energy transition

Significant shifts have taken place in energy technologies during the past two years. Some of these have more to do with the UK's economic and policy context than technology developments per se. But progress in a few areas of research and development have influenced forecasts for the application of energy technologies and the mix of resources compared with those mapped out in 2010.

Three factors have had a major impact on the development of energy technologies: the absence of robust economic growth, notably in Western economies; the boost in shale gas production, particularly in the US;[137] and the Fukushima nuclear disaster.

The question of how to make renewables affordable in the current economic climate has become a central concern for industry as well as for governments. Bioenergy is now put forward as a cheap way of capturing carbon.[138,139,140] Progress has been made on mapping out a hydrogen alternative to the electric battery vehicle, but both hydrogen and electric batteries will be expensive. The fact that a hydrogen plant could provide transport fuel *and* generate electricity is now considered a double-value proposition.

Together with cost, the public acceptability of certain technologies is now more evident. Nuclear energy is less controversial in the UK than it has been in the past,[141] despite Fukushima, but there are environmental concerns about carbon storage[142] and shale gas 'fracking'.[143] Privacy

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[137] http://www.raeng.org.uk/news/publications/list/reports/Shale_Gas.pdf
[138] http://www.bnef.com/PressReleases/view/188
[139] www.tyndall.ac.uk/sites/default/files/twp147.pdf
[140] http://www.bioforsk.no/ikbViewer/Content/36501/Skjanes%20et%20al%202007%20BioEng.pdf
[141] http://www.ipsos-mori.com/researchpublications/researcharchive/2903/Nuclear-Energy-Update-Poll.aspx
[142] http://ec.europa.eu/public_opinion/archives/ebs/ebs_364_en.pdf
[143] http://www.guardian.co.uk/money/2012/jun/23/fracking-undermine-value-home

and security concerns have also been expressed over access to and protection of customer data, which may be required for smart meters if they are to achieve significant impact on energy use.[144]

Bioenergy and 'negative emissions'

One area of research is exploring the potential for improving energy crop yields, particularly of woody/grassy crops suited to UK conditions. The BBSRC's Sustainable Bioenergy Centre,[145] a virtual centre of six UK academic research groups created in 2009, is focusing on the biochemical bioenergy pipeline from growing biomass through to conversion of biomass to bioenergy, while the EPSRC's SUPERGEN Bioenergy Hub[146] addresses thermochemical conversion processes.

Others view CO_2 as a potential energy feedstock rather than a source of pollution, suggesting that CCS might be complemented by, or even in time replaced by carbon capture and conversion.[147] Imitating natural photosynthesis, the goal is to turn CO_2 into high-energy carbon compounds. The high-energy electrons needed for such a conversion to take place could be derived from several sources: wind, wave, tidal, hydro, nuclear, solar PV, or even an artificial leaf system,a device that turns the energy of sunlight directly into a chemical fuel that can be stored and used later as an energy source.[148,149] The technology requires cheap and robust catalysts that can work at very high efficiencies. The USA supports such efforts via the Department of Energy,[150] and other countries such as Germany, China and Japan also fund research in this area. The UK has academic strengths in the area of electrochemical catalysis that may prove to be the source of innovations and commercial success in this field.

The US Department of Energy programme 'Innovative Concepts for Beneficial Reuse of Carbon Dioxide' supports projects looking at ways of converting captured CO_2 emissions into products such as fuel, plastics, cement and fertilisers: six projects made it through to phase 2 testing in July 2010.[151] Other approaches include using CO_2 to make polymers[152]and to carbonate 'red

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[144]http://www.fas.org/sgp/crs/misc/R42338.pdf
[145]http://www.bbsrc.ac.uk/research/biotechnology-bioenergy/bsbec/bsbec-index.aspx
[146]http://www.supergen-bioenergy.net/
[147]Summary of the joint seminar of BMBF and Siemens (2009), http://www.fona.de/CO2-seminar/co2_bmbf.pdf
[148]http://www3.imperial.ac.uk/energyfutureslab/research/grandchallenges/artificialleaf
[149] http://www.nature.com/news/2011/110929/full/news.2011.564.html
[150]JCAP initiative http://jcap.caltech.edu/
[151]http://fossil.energy.gov/recovery/projects/beneficial_reuse.html
[152]http://www.icis.com/Articles/2011/10/17/9500368/innovation-awards-polymers-put-co2-to-use.html

mud', the bauxite ore slurry from alumina extraction, which can be then used as aggregate material for mine reclamation and to amend acidic soils.[153]

Backing up intermittent power supplies

One proposed novel system to meet the intermittency challenge involves the constant operation of a coal gasification plant with pre-combustion CCS, feeding a closed cycle gas turbine for electricity generation. This uses a 'swing' technique to enable the hydrogen from the gasification process either to be stored when the back-up power is not required or alternatively used to make commercial products such as ammonia.[154]

New energy storage systems will play a role in providing back-up, particularly those that can decouple power output and storage capacity. Work on flow battery technology is taking place at Imperial College London and at Southampton and Manchester Universities, while sodium ion batteries are being researched at St Andrews and Cambridge. Another approach, offered by Highview Power Storage, uses liquid nitrogen to store energy, which is released by bringing the nitrogen back to ambient temperature.[155]

Real-time power grid simulation and the HVDC grid

Together with the USA, China and Canada, the UK is a world leader in power electronics and real-time systems simulation. Simulation is particularly important for power grids, where real-time experiments are not practical. Real-time power grid simulations can also be used to explore some of the challenges to do with energy storage by including batteries in the simulation model, and they will be useful in designing and testing smart grid concepts and operating strategies.

An emerging area where simulation is important is high-voltage direct current (HVDC) grids, already being developed as a transmission mechanism for offshore wind energy, and which are likely in time to replace parts of existing alternating current (AC) grids.[156] Such systems provide higher efficiency, more flexible control and a reduced need for physical connection components, added to which many domestic appliances run on direct current (DC) rather than AC. The UK is

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[153] http://www.globalccsinstitute.com/community/blogs/authors/martinoettinger/2011/06/29/re-using-co2-adding-value-permanent-capture
[154] www.havenupdate.com/index.php/download_file/view/1959/401/
[155] http://www.theengineer.co.uk/sectors/energy-and-environment/news/cryogenic-energy-storage-plant-could-provide-valuable-back-up/1007539.article
[156] http://www.ft.com/cms/s/0/82d5e2d2-259e-11e1-9c76-00144feabdc0.html#axzz20gP97NW2

active in an EU Framework 7 project looking at the research and development challenges associated with the integration and coordinated operation of EU and Russian power grids.[157]

3.2 On demand

As technology erodes the dominance of the 20th century centralised production, mass market economy, new actors are emerging, while some traditional actors are finding a new role. In areas such as the digital spheres of music, film and fashion, individual preferences have a direct influence on products. In other areas, in which industrial scale is still important, the innovation actors may be clubs, associations, user groups, or parts of local government and regional partnerships.

Bodies such as city authorities, business networks and consumer groups are starting to take a greater interest in designing services that meet the needs of citizens in their region and improve their quality of life. This movement supports local businesses, fosters innovation and contributes to balancing growth across regions: mobile technologies and social networks enable collaboration between the various parties.

Meanwhile businesses, particularly those looking to achieve scale in new markets, are attracted by the idea of contracting with a municipality: Philips' CEO wants to 'sell LED lighting to cities'.[158] On the procurement side, city leaders may start to ask 'Why can't I represent 100,000 of my citizens and negotiate a deal?', for example on energy supply.

Service robotics

One field being redefined by the emphasis on meeting customers' needs, rather than simply increasing productivity, is robotics. No longer confined to tasks in which they either replace human labour or carry out tasks, such as assembly of miniaturised components, robots are becoming service providers *alongside* humans in fields such as healthcare, rehabilitation, surgery and consumer products.[159] These are contexts in which they are required to adapt to circumstances rather than slavishly repeating a series of actions. In agriculture, for example, innovative applications have been developed, from weed control systems to a robotic arm that allows cows to be milked and fed on demand.[160]

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[157] http://www.icoeur.eu/
[158] http://thecleanrevolution.org/_assets/files/LED_report_web1.pdf
[159] http://www.robotics-platform.eu/cms/upload/SRA/2010-06_SRA_A4_low.pdf
[160] http://www.iagre.org/sites/iagre.org/files/repository/IAgrEGlobal_Food_Security_WEB.pdf

Staking a claim to be the 'true enabling technology' of the 21st century, robotics sees its role as the launch pad for many new businesses. Europe is the world's leading robotics region, and, despite the fact that in the UK the field has had to work to gain recognition, occasionally being overshadowed by information and communications technology (ICT) and engineering, expertise is still strong in British universities and the UK plays an important role in EU projects: Bristol has recently been selected as the possible location of one of three new EU robotics knowledge and innovation centres.[161]

Significant opportunities lie ahead for the industry: demand in the healthcare and care industries is likely to increase with an ageing population and increased provision of care at home or in the community: the next generation of robots is likely to have enhanced capabilities in reading, grasping and poise that make their presence among humans natural as well as valuable, and they will need to continue to develop new forms of 'social intelligence' in order that people can interact with them intuitively and safely.

Increasingly, robotic capabilities will be extended to living tissues, as advances in artificial muscle and cartilage[162] converge with progress in prosthesis and augmentation technologies[163] and eventually interface with discoveries in cognitive science.

3.3 Human-centred design

The move towards human-centred design is driven by similar factors and trends and enabled by similar advances in technology as the 'on demand' theme:

- An abundance of mass-produced consumer products leading to saturation,
- A desire for personalised products and services,
- An 'experience culture' developing at the expense of the acquisition and ownership culture,
- Digitisation and an information-based economy, leading to reproducibility at minimal or zero marginal cost,
- A move towards ambient intelligence and ubiquitous computing power.

Design expresses a desire to shape materials and the environment to satisfy human expectations and desires. Until recently, both materials and the environment could be treated as

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[161] http://www.eurobotics-project.eu/cms/upload/Publications/euRobotics_ISR_2010.pdf
[162] http://www.newscientist.com/article/dn16849-artificial-cartilage-performs-better-than-the-real-thing.html
[163] http://neurobotics.cs.washington.edu/papers/RAMArticle.pdf

inert and unresponsive. This is now changing: new types of materials have startling properties – either on account of their atomic structure or because of the mixture of composite elements contained within them. For example, designing materials from the microstructure up can confer optical, magnetic and electronic properties. And the environment is starting to become 'intelligent', in other words capable of sending, receiving and processing data.

Human-centred design injects creative purpose into an environment imbued with increasingly pervasive 'calm' or intelligent technologies: it is 'design led, needs driven and technology anchored'. The key requirement to succeed in this area is for designers to explore applications *together with* technology users: in the past companies have developed technologies, applications for which have taken a long time to be discovered (for example, ICI discovered polyethylene in the 1930s, but its applications only started to become mainstream in the 1950s). Companies such as Philips and Electrolux today employ people specifically to work on 'weak signal' ideas.

Intelligent clothing

At the threshold between our bodies and the environment, clothing is an obvious communication 'membrane': information from the body can be transmitted outwards, while ambient signals are received at this interface and processed. Early efforts at 'smart' clothing however were not practical, in part because their purpose was unclear,but both technology and design have improved to the point at which creative designers are now working with technologists to provide solutions to real problems:

- Anticipatory devices that warn of an imminent fall are being incorporated in fashion fabrics,[164]
- Northumbria University's London Design Centre is working with NASA to develop space apparel,[165]
- Adding and evaporating colour dyes is a major contributor to energy use; researchers at BASF and elsewhere are investigating how changes to materials at the nano-scale can be used to create 'structured colour' (in line with the broader economic shift from energy-intensive to information-intensive products).[166]

Trends towards ambient intelligence in the built environment are highly significant for the move towards e-health and point-of-care services, particularly given ageing populations. Monitoring

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[164] http://www.bcs.org/content/conWebDoc/14354
[165] http://www.northumbria.ac.uk/sd/academic/scd/research/themes/makingsense/themes/activematerialsforliving/
[166] http://www.packaging.basf.com/p02/Packaging/en_GB/content/products/Farbe_ohne_Farbstoff

both in people’s homes and outside should improve health outcomes while freeing people from the need to carry intrusive devices.

Sensor technologies

Sensor technologies are a key element of this new design. Adidas, for example, is investing in the development of sensor-enabled products,[167] and exploring related business models that are likely to take the company away from its perceived core business.

Another promising area is biosensors and bioreceptors, particularly a new generation that are attached to graphitic surfaces and highly sensitive to disease biomarkers.[168] The combination of this technology with mobile communications promises hand-held devices for human health monitoring but also has important applications in agriculture. Also in agriculture, mobile technology combined with hyperspectral imaging techniques can be used for the rapid identification of plant health problems,[169] and progress in this field should make such diagnostic devices affordable for smallholder and subsistence farmers.

3.4 Conclusions

This overview of promising technologies demonstrates some of the huge potential of science and technology to generate economic growth, as well as addressing some of the big questions facing our global society, such as how to address the challenges of climate change and resource scarcity through making best use of resources, recycling, changing the energy mix to include renewables, and reducing our carbon use in everything from buildings to transport. The UK has an opportunity to take a lead on this global energy transition.

The UK research base has played a key role in the development of new materials, such as graphene, and in the design of materials at a molecular level to provide additional functionality such as optical, magnetic and electronic properties over and above their structural properties. With investment in this area, the UK could position itself to lead a 21st century manufacturing revolution, fuelled by new technologies such as those discussed here, with local ‘on-demand’ manufacturing using 3D printing technology and a move towards product *plus* service commercial models – ‘servicisation’.

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[167] http://www.telegraph.co.uk/sport/football/8797144/Adidas-launches-football-boot-with-a-brain.html
[168] www.ncbi.nlm.nih.gov/pubmed/22051545
[169] http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3274483/?tool=pubmed

The UK government will have a key role to play in supporting these and other technologies, from providing direct support to generating the right environment for investors through a stable and consistent regulatory framework. The government can also do more to broker relationships between research and industry to encourage new ideas to be translated into successful commercial outcomes. Finally, the government can intervene helpfully to counter ill-informed criticism while taking seriously its role in protecting our society from any threat, and help to communicate how exciting and transformative these new technologies can and will be over the coming 20 years.

Annex 1: List of contributors

It is inevitable in a project with such a broad scope and large number of contributors that people on occasion hold different views, for example on how certain technologies will develop. The Foresight Horizon Scanning Centre aimed to reflect the balance of these views in the 2010 report and again in the 2012 Refresh, signalling when they were not widely shared.

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URN 12/1157 Technology and innovation futures