Technology and Innovation Futures

Technology Annex

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This Annex gives information summarising each of the technologies, derived from the workshops, the interviews and desk research. These have been grouped together in the 28 clusters noted in Section 4 of the main body of this report, and underpin the seven broader cross-cutting areas described in Section 2.

The Technology Annex consists of 55 entries on specific future technologies and innovations, loosely grouped into the four areas of Materials and Nanotechnologies; Biotech and Pharmaceuticals; and Digital and Networks, corresponding to the individual workshops held on these areas. For each of the technologies, comparable information is provided (when available) on the size of the potential market in 2025, the disruptive potential of the technology, UK capability, and barriers and enablers. Although augmented with deskwork, the information contained within the Annex is not intended to be comprehensive. The choice of material and the emphasis on particular areas reflects the expertise of the participants in the interviews and the workshops and the nature of the discussion at the latter.

Contents

Materials and Nanotechnologies

1.1 3D Printing and Personal Fabrication

Abstract

Ink-jet technology could give individuals the power to manufacture their own products. This idea has significant implications for high-tech customisation, for developing 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 effects on the transport industry, including a reduction in its fuel use. Home fabricated goods would have a small embedded carbon footprint, provided the raw materials for them were produced locally. It could make a vast range of products from transplant organs to solar power-gathering materials simple and cheaper to produce[1].

Summary

The first technology for **3D printing, sterolithography**, was developed in the mid-late 1980s[2] and allowed 3D computer aided design (CAD) models to be fabricated using the sequential, or additive, layering of solidified photopolymers to reconstruct the 3D shape.

Subsequently alternative techniques have been developed that allow 3D printing of a range of substrates. The choice of a particular technology is usually dependent on the required materials for printing, accuracy, material finish, material strength, cost and the speed of construction. Additional successfully commercialised technologies include **fused deposition modelling** which works by additive layering of a thermoplastic material; **selective layer sintering** where a CO_2 layer is used to bind powders to produce solid structures; 3D printing utilising inkjet printing technology accurately to deposit a liquid binder; and **polyjet** or **polyjet matrix** printing which allows multiple materials to be deposited simultaneously, typically photopolymers before solidifying with UV lasers.

3D printing techniques have been utilised for a range of applications from product design, manufacturing, building biological tissues and large-scale housing production. Ink-jet 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 ink-jet technology to print simple electronics, and for 3D printing of simple structures and prototypes of products.

Ink-jet manufacturing also appeals to the computer industry for several reasons. Its low cost and easy setup, the ease with which it can be customised, and its ability to use new classes of inks and substrates make it attractive for radical experimentation. It is already used in the fabrication of flexible electronics and displays.

In manufacturing, 3D printing has already impacted the development of printable materials for electronics, for instance to reduce the cost of solar power. The Japanese company Fujifilm said in 2008 that it uses a Dimatix Materials Printer (DMP) to fabricate solar cells. The company claims comparable results to the use of clean-room technology, with lower costs. The printer uses cartridges which can hold a range of raw materials. Konarka Technologies is also involved in ink-jet technology, using Fujifilm's DMP equipment.

Research is underway to increase the range of materials that 3D printing technologies can use. There has been recent progress in printing glass[3] and complex plastics[4]; however, the ability to print electronic components is still limited, although this is an area of significant interest. Advances in nanoscale electronic components, such as nanocapacitors and logic gates would circumvent the issues with depositing larger components. Research is also underway for the 3D printing and assembly of nanostructures, both for functional components and to act as scaffolds; for instance, research at MIT aims to build DNA microarrays and nano devices for diagnostics of genetic diseases[5].

3D organ printing techniques[6] have also been developed that use different techniques to automate construction of 3D structures. Organ printing involves deposition of sequential layers of gels containing cells or aggregates onto gel paper to build a 3D structure. The gel is then dissolved to give rise to the functional tissues or organs.

3D printing techniques have also been scaled up to allow construction of large structures: the first 3D-printed building has been constructed by D-shape[7], a company which utilises granular sand to generate artificial sandstone structures, with reduced construction times and costs.

There is defence interest in printing patterns of conductive materials to be incorporated into layered composites which then act as radar absorbing materials – these are called **circuit analogue absorbers**. The aerospace industry is showing a lot of interest in the manufacture of complex parts. Airbus has done some work to evaluate the technology but is not using it currently in production. The US military has looked at **Additive Layer Manufacturing** (ALM) for in-theatre spares production and has trialled a trailer with the kit in.

At present 3D printing technologies cost in the order of tens of thousands of pounds, a price that delays the advent of **personal fabrication**; however as prices fall ink-jet technology could give individuals the power to manufacture their own products. Existing open-source projects, including RepRap,[8] and Fab@Home,[9] are also aiding the mass adoption of technologies by allowing users to build their own 3D printing devices for around £350,[10] and sharing printing expertise.

Personal fabrication has significant implications for product customisation and new models of distributing manufacturing. Ink-jet technology would significantly reduce the need to transport finished goods around the world, with substantial effects on the transport industry, including a reduction in fuel use. Home-fabricated goods would have a small carbon footprint, provided the raw materials used to make them were produced locally. The technology could be used to make a vast range of products, from domestic goods to simple and cheap solar energy devices.

Size of Market to 2025

The global market has been estimated to be $782.6 million in 2013.[11]

Disruptive Potential

The mass-commercialisation of 3D printing could transform current models of manufacturing, facilitating a move towards distributed manufacturing and increased personal customisation of products. For industry, advances in printing technology that allowed low-cost printing of electronics could drive down the cost of consumer electronics. In addition, 3D printing technology could move into non-traditional fields including rapid prototyping of food.[12]

A disruptive technology within 3D printing would be to have multi-axis deposition and the removal of the need for multiple materials.

Trends

The cost of commercial 3D printers has fallen from £500,000 in 1999 to around £15,000.
HP signed a deal with Stratasys aiming to capture 70% of the global 3D printing market.[13]

Barriers and Enablers

Barriers:
The cost of current technologies is prohibitive.
Lack of open standards.
Cost of raw materials.
Lack of nanotoxicologists.

Enabler:
Consumer desire for low-cost and customised goods.

Applications

Manufacturing – construction of complex structures, low-cost printing of flexible displays and electronics, nanostructures, biological constructs, tissues, DNA computing.
Design – custom models.
Personal fabrication.
Food.

UK capability

The UK has significant research and commercial experience in this area, with strengths in materials, design and manufacturing processes. A number of centres have strong expertise, both demonstrators and commercial, including PETEC and RCA. The SME community is also very active.

US strong in cutting edge – MIT
Large multinationals investing significantly in distribution of 3D printers.

Institutions

- Epson (UK)
- University of Bath – the RepRap project on open source 3D desktop printing[14]
- University College, London
- University of Cambridge
- University of Manchester
- Boxford (UK manufacturer)
- Motorola Orgatronics (Netherlands)
- Fujifilm

- Konarka Technologies
- ESA

1.2 Building and Construction Materials

Abstract

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, improvements in supply chains and up-skilling the workforce as well as through technological innovation in a number of areas.

Summary

The UK construction industry is facing increased pressure to develop sustainable and low-carbon methods of construction as the UK moves towards a low-carbon economy. The UK Low Carbon Transition Plan[15] has set three carbon budgets through to 2050, requiring a 26% reduction of CO_2 emissions by 2020, and an 80% reduction by 2050.

The construction industry in the UK will be required to adapt and contribute to these targets including: a 29% reduction of heating emissions in residential buildings, with all new builds being carbon neutral from 2016; a 13% reduction in emissions from non-domestic buildings with zero-carbon new builds in the public and private sector from 2018 and 2019 respectively; construction of new energy infrastructures, including a smart grid; and infrastructure to deliver a 14% reduction in transport emissions by 2020.[16]

The use of fibrous composite materials is likely to be one of the major changes in this sector in the next decade. The reduced costs and high performance of glass and carbon composites, together with low maintenance, are beginning to make them competitive. There is research currently looking at use of these materials, e.g. 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.

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 Holcim and Novacem, are already developing low-CO_2 concrete. New materials will play a role in meeting the targets. For instance, composites offer a new wave of high performance materials. Recent examples include concrete embedded with carbon and polyvinyl-alcohol fibres.

These composite concretes have improved compressive capacities and flexural strengths.

Nanotechnology also plays an increasing role in construction materials (but see note on cost in the Barriers section below). Two nano-sized particles that stand out in their application to construction materials are titanium dioxide (TiO_2) and carbon nanotubes (CNTs). 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 (see section 1.5). CNTs can be used to strengthen and monitor concrete.

Active surfaces. Meanwhile, self-healing materials, such as concrete and paint, could become more widespread over the next 10 years. These would increase the durability and longevity of buildings.

Sustainable construction – including the use of efficient electrical appliances and heating installations – can also make a major contribution to saving energy and reducing emissions.

With the public sector accounting for up to 40% of demand for construction, public procurement could push demand towards innovation-oriented materials. The introduction of lifecycle and cost-benefit assessments could facilitate the procurement of sustainable construction works by public authorities.[17]

Size of Market to 2025

The construction industry represents 9% of UK GDP and employs 2.6 million people.[18]

Disruptive Potential

The UK Government's Low Carbon Industrial Growth Team has estimated that the construction industry can influence 306Mt of CO_2 emissions, corresponding to just under half of total UK emissions. This includes both inherent emissions within the construction industry and emissions associated with use of buildings, which can be addressed by developing building solutions to alter users' behaviour.

Barriers and Enablers

Barriers:
Perceived inertia in industry and 'circle of blame' between clients and industry.
Lack of standardised design, transparency and need for further standards, e.g. the Code for Sustainable homes.

Absence of consumer demand.
Costs of nanomaterials may be a barrier to early use in an industry that is still struggling to see the advantages of carbon fibre (even though that is much cheaper than it was a decade ago).
Construction is, essentially, a low-cost industry so take-up of expensive self-healing materials may also be slow, although self-healing paints may be an exception.

Enablers:
Commitment to meeting carbon emission targets.
Increasing price of electricity.

1.3 Carbon Nanotubes and Graphene

Abstract

A range of carbon-based nanomaterials exists with applications in molecular electronics, sensing, micro- and nano-electronic mechanical systems, and energy. 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.

Summary

Graphene and carbon nanotubes have received a lot of media attention. **Graphene** is a two-dimensional structure of carbon packed into a honeycomb lattice, like a single isolated layer of graphite.[19] The structure of grapheme gives it interesting electronic properties; in particular the zero-mass of its electrons promises rapid conduction of electricity at room temperature, estimated at 100 times that of silicon, with applications for high-speed devices that could replace silicon-based technologies.[20] The use of graphene in technologies such as transistors was originally limited as graphene does not naturally have a band-gap. However, researchers have shown that a band-gap can be induced and tuned in graphene using magnetic fields, allowing the development of graphene-based transistors.[21,22,23] Other potential applications include chemical sensing instruments, biosensors, ultracapacitance devices, and flexible displays.[24]

One of the barriers to uptake of graphene technologies has been scalability and reliability of manufacture. New techniques, however, have succeeded in producing high quality and relatively large (tens of centimetres[25]) sheets of graphene.[26]

Recent advances have also suggested promising applications for graphene in fast DNA sequencing[27] and for remediation of arsenic, where a reduced graphene oxide is combined with magnetite to create a superparamagnetic hybrid capable of extracting arsenic from water.[28]

Carbon nanotubes (CNTs) may be considered extended tubes of rolled **graphene** sheets. CNTs are extremely strong, 100 times the tensile strength of steel, very light and of low density. Polymer composite materials made from CNTs offer opportunities for lighter and stronger manufacturing. CNT-reinforced polymer (CNRP) composites are of particular interest to the transportation industry, especially to manufacturers of commercial aircraft and space vehicles. Simulations and models have demonstrated improved fuel efficiency and flight range for hypothetical aircraft made from CNRP composites. CNRP composites could also enable more radical changes to aircraft design, including ‘morphing wings’ that change size and shape, maximising a plane‘s efficiency as its speed changes.

In spacecraft, NASA has worked to develop composite films called Polymer-Single Wall Carbon Nanotube Composites (SWNTs). These may have a range of desirable properties in addition to lighter weight, including radiation resistance, resistance to atomic oxygen, which is valuable in low-Earth orbits such as that used by the International Space Station, and tear resistance, which is valuable because of the hazards of impacts with meteorites and space debris.

Nanotubes may be a lighter and higher-performance replacement for carbon fibre, however the cost of nanotubes currently limits their advantages over standard composites. Early uses may be in yachts and racing bicycles as well as racing cars, applications where price is a secondary consideration to performance.

CNTs may help power the vehicles of the future as well as making up their structural components. It has been shown to be possible to produce nanotube capacitors that can store approximately as much electrical power as a battery and which have shorter discharge and recharge times, while research at MIT has shown that a tenfold increase in the power of lithium batteries can be achieved by using carbon nanotubes as an electrode. In other trials, CNTs have been used to store hydrogen, a possible fuel of the future, with high efficiency.

Much of the mass of a vehicle is taken up with equipment. There is scope for carbon nanotubes to achieve massive weight savings. For example, a simple nanotube structure has been constructed which can receive radio waves and turn them into sound – in effect it is a radio that fits onto a pinhead. Similar technology has been use to develop speakers that would allow submarines to operate sonar undetected.[29]

More speculatively, CNTs hold the possibility of building a ‘space elevator’ anchored to Earth in the Pacific, perhaps 100,000km high.[30]A trial lift has performed successfully up to 300 metres off the ground. Carbon nanotubes are one of the few materials that might allow the space elevator to be built without collapsing under its own weight.[31]

Buckminsterfullerene (Buckyballs or C60) is another carbon-based nanostructure that consists of a closed sphere of carbon atoms with unique strength and antioxidant properties. Applications include addition to polymers, development of efficient fuel cell membranes and drug delivery. A large chemistry has developed around fullerenes since their discovery in the 1980s, but so far, despite their remarkable physical and chemical properties suggesting wide application in catalysis, chemical synthesis, gas separation and purification, difficulties of scaling up production has largely confined their use to laboratories.

As with many technologies, the benefits that could be derived from nanotechnologies have possible risks attached. Concerns over carbon nanomaterials include whether CNTs might present similar risks to asbestos,[32] and whether C60 is toxic to cells.[33]

Trends

Fiat has taken out a patent on the use of carbon nanotubes in motor vehicle components, to produce parts which have integrated sensor ability. The patent mentions fuel tanks, pipes, seats and bumpers as possible applications.

Extensive use of carbon composites in next-generation aircraft, notably the Boeing 787 and Airbus A380.

Barriers and Enablers

Barriers

As CNT whiskers are short, the only way to use them is to mix them with resins, but these become too viscous to use once fibre content gets above a few percent – at which point structural performance is greatly inferior to carbon fibre composites. Continuous aligned CNTs – like a textile fibre – may provide the solution in 10-20 years.

Institutions and Applications

- University of Manchester – work of Andre Geim – graphene
- University of California at Santa Barbara
- MITRE Corporation – simulation and modelling of vehicles constructed from CNRP composites
- Hyperion Catalysis – CNT manufacturing
- NEC – CNTs as electrodes for fuel cells
- LiftPort – Space Elevator plan and also sells nanotubes
- Thomas Swan and Co. – UK firm in nanotube joint venture with Cambridge

- University of Cambridge, Materials Science and Metallurgy
- University of Oxford Nanotube Group
- Imperial College

1.4 Metamaterials

Abstract

Metamaterials are artificial materials that provide the ability to engineer material properties beyond those achieved from conventional materials and composites.[34] The material properties of relevance are those that define the manner in which materials influence a propagating wave. Light (electromagnetic waves, including micro-waves) and sound waves are the two most recognised types of wave, but others include blast, seismic, matter and gravitational waves. Applications in five years' time include smaller, lighter and better-performing antenna and other microwave components, but the possibility of the 'Harry Potter invisibility cloak' remains distant.

Summary

The new properties exhibited by metamaterials stem from rational design at length-scales larger than atoms and molecules, but smaller than the wavelength of the interacting wave energy. Using the spatial variation of material types and properties on these length-scales provides advances in known devices, systems and capability, as well as the potential for a disruptive advance enabling new devices and functionality. At present, metamaterials are typically created by periodic arrangements of one material in another (for example, in the case of electromagnetic waves metallic elements in a dielectric, or air voids in a dielectric); although future trends will be towards a periodic arrangement of the materials and further size reduction compared to the wavelength.

Work is still at the very fundamental stage, but trends in terms of exploitation may be quantified with 5, 10 and beyond-15-year horizons. In five years applications will be use passive metamaterials to yield antennas and microwave components (such as couplers, filters and delay lines) that are smaller and lighter and exhibit improved in- and out-of-band performance, and improved optical coatings for filtering or absorption. In 10 years applications in antennas will be extended to wide-band multifunction performance using tuneable metamaterials: the technical challenges regarding losses in and the fabrication of optical metamaterials are likely to have been sufficiently resolved to enable a wide range of device applications relating to optical communications and computing, as well as to higher efficiency solar energy generation. In the long term, reconfigurable electromagnetic surfaces and structures may become feasible, enabling completely new sensors

and levels of functionality; but the achievement of full broadband cloaking remains a distant possibility.

Past and Current Trends

Metamaterials emerged as a potentially disruptive technology in 2000,[35] although the concepts represent an evolution from the work on artificial dielectrics of more than a century ago and more specifically and recently related to frequency selective surfaces. In this field, more than 1000 new scientific research articles are now being published every year.

Disruptive Potential

A new design approach has been inspired by the practical realisation of metamaterial effects such as negative refraction and the perfect lens for near-field imaging with resolution below the diffraction limit; this is Transformational Optics design[36,37] which has already led to the pioneering concepts for cloaking.[38] This new design approach has the potential to connect the optimal spatial variation of material properties within an object, coating or device with the resultant macroscopic influence on an incident and scattered wave.

Over the coming years, coupled with advances in computational resources, this is likely to lead to a step-improvement in the optimal design of metamaterials and to an artificial material analogue of the periodic table, leading to an understanding of engineering meta-materials that is potentially as rich as the chemistry based on naturally occurring elements. Advanced fabrication technologies over a range of length-scales, including the micro-nano, are critical enablers for the full exploitation of metamaterial potential. The development of metamaterials from terahertz, through the infrared and into the optical band, is current attracting much research interest; from a fabrication perspective it is the most challenging, but this area has the potential for very significant reward.

UK capability

Institutions

Professor Sir John Pendry, and his group at Imperial College London, has played a leading role in this field; but there has been substantial global research investment in the field underpinning the now extensive body of published literature. Many university groups, institutions, companies and agencies work in the field, and the following list is restricted to recent and current UK projects:

- Meta, micro and nano technologies – Dstl (MOD-funded)
- Advanced Materials for Ubiquitous Leading-edge Electromagnetic Technologies (AMULET) – ERA Technology, NPL, QMUL, Vector Fields (TSB-funded, £3.4m)
- Metamaterials and electromagnetic fields – Imperial College London, University of Southampton (Leverhulme Trust)
- Nanostructured photonic metamaterials – University of Southampton (EPSRC)
- New theoretical tools for metamaterial design – University of St. Andrews (EPSRC)
- Active Plasmonics: Electronic and All-optical Control of Photonic Signals on Sub-wavelength Scales – Imperial College London (EPSRC)
- Active Plasmonics and Perfect Lenses with Quantum Metamaterials – Imperial College London (EPSRC)
- Antennas for Healthcare and Imaging – QMUL (EPSRC)
- Active Plasmonics and Lossless Metamaterials – University of Surrey (EPSRC)
- Aerogels in Fibre-Optics – University of Bath (EPSRC)
- Detailed study of zigzag metal gratings – University of Exeter (EPSRC)
- Nanostructured metafilms: a new paradigm for photonics – University of Southampton (EPSRC)
- The Casimir Force in Complex Topologies and its Utility in Nanomachines – Universities of Sheffield, Birmingham and Leicester (EPSRC)
- Semiconducting and superconducting nano-devices to control terahertz radiation: emitters, filters, detectors, amplifiers and lenses – Loughborough University (EPSRC)
- Computational differential geometry applied to invisibility cloaks in electromagnetism and elastodynamics – University of Liverpool (EPSRC)
- High Performance RF Metamaterials – Imperial College London (EPSRC)
- Advanced Design and Control of Active and Passive Metamaterials: from Microwaves to Optics – University of Salford (EPSRC)

- Negative index metamaterials for visible-light optics – University of Manchester (EPSRC)
- Biomimetic hybrid semiconductor photovoltaic devices – University of Sheffield (EPSRC)
- Characterisation and Implementation Of Left-Handed Meta-Materials In Electromagnetic Crystal Structures – QMUL (EPSRC-MOD)
- Metamaterials Create New Horizons in Electromagnetism – Imperial College London (EPSRC)
- NSF-EPSRC Materials Programme: Novel nonlinear photonic metamaterials based on metallic nanostructures – QUB (NSF-EPSRC)

1.5 Nanomaterials

Abstract

The physical properties of nanoparticles are unique, giving them broad potential applications in catalysis, electronic devices and medicine. There are some grounds for caution in developing these uses, as nanoparticles may have an impact on health and the environment.

Summary

Nanomaterials are often conventional (metals, ceramics, semi-conductors etc), sometimes new ($carbon_{60}$), and novel structures (wires, tubes, coatings, spheres, etc.) whose mechanical, electrical, reactivity and other fundamental properties are changed on account of the increased relative surface area of exposed material. Nanomaterials differ from ‘bulk materials’ in their properties because of surface effects and because quantum effects become significant at the small scales involved.

The properties that nanoparticles exhibit are often size-dependent; for instance, as materials approach the nano-scale they have an increasingly high surface-area-to-volume ratio, with a significant number of atoms at the surface of the material. This can, for instance, greatly affect their reactivity. Additional properties include quantum refinement, localised surface Plasmon resonance, superparamagnetism and ferrofluidity.

Quantum confinement is a phenomenon whereby electrons are trapped in a small area. Confinement can occur in one, two or three dimensions with different applications. The degree of confinement in nanostructures is determined by their size and shape. **Quantum dots** are confined in three dimensions and act as semiconductors. Their advantage over traditional semiconductors is that their band-gap is dependent on the size of the particles. They have a wide range of applications; for instance, in photovoltaic cells they promise improved efficiency as energy could be captured from a broader spectrum of light than currently possible. Significant opportunities also exist in the application of quantum dots in electronics, for ultra-low power computing,[39] ultra-thin displays, photonics, image sensors and efficient and more powerful semi-conductor lasers.[40] Additional applications include optical probes for medical imaging.

Quantum sensors, and other devices drawing on the phenomenon of quantum entanglement, may find a range of applications, including covert range finding and imaging, 'on-line' image processing and object recognition, and high sensitivity sensing of, for example, magnetic anomalies. Applications in **spintronic** devices is already well-established (e.g. hard disk read-heads and non-volatile memory devices), but there is still huge potential for further development.

Localised surface plasmon resonance is a phenomenon whereby electromagnetic waves propagate parallel to the surface boundary of metal nanoparticles. This resonance is susceptible to disturbances, such as molecular adsorption, allowing nanoparticles to be utilised as molecular and chemical sensors; for instance, a test capable of detecting a few molecules of cancer biomarkers has been developed using specific structures of gold nanoparticles.[41]

At the nanoscale the magnetic fields of particles are capable of aligning to form very large magnetic fields capable of reversing direction at high rates and at ambient temperatures, termed **superparamagnetism**. Biomedical applications include MRI contrast agents, improving imaging resolution,[42]targeting of nanoparticles for drug delivery, targeting and destroying tumour cells,[43] as well as purification of DNA in molecular biology.[44]Superparamagnetism can also be utilised in the electronics industry in solid-state devices, spintronics[45] and mobile electronic applications.[46]

Ferrofluidity consists of magnetic nanoparticles coated with surfactant suspended in a liquid. Ferrofluids have been used commercially since the 1960s as sealants, for instance in magnetic disk drives and in audio speakers to improve heat-transfer. However, research is underway into the development of magnetic micro- and nano-electronic devices (MEMS/NEMS).[47] Additional existing uses include magnetic lubricants and the radar-absorbent paint used in stealth technology.[48]

Some particles also exhibit specific properties, such as zinc oxide which is photostable and can be used to block UV light, and TiO_2 which can self-clean (see Section 1.2).

Carbon nanotubes, tubes of pure carbon with lengths of up to a few millimetres, walls one atom thick and diameters of around 1-100 nm, are among the structures used in various nanotechnological applications (see Section 1.3).

The ability to measure and characterise materials at nanoscale underpins all science and technology in this area, and is critical to the development of standards and regulations which can speed up or slow the rate of uptake.

New developments in manufacturing, ‘molecular manufacturing’, linked to developments in materials, may also offer significant performance gains and/or cost savings from reduced raw material use. They could also lead to increased automation in manufacturing, increased build accuracy and reduced maintenance costs. Nanomaterials could offer ‘green benefits’, including lower energy consumption in both manufacture and use, reduced waste, reduced use or generation of environmentally harmful substances and greater reuse of materials. However, the properties of nanomaterials that produce these benefits and opportunities may also bring environmental, health, safety and other risks, which need to be anticipated and monitored.

Several trends have stimulated the appearance of nanomaterials. In electronic engineering, steady reductions in the size of electrical components on silicon-chip circuits have reached the point where wires, transistors and other items are now typically no more than a few tens of nanometres thick in one or more dimension. This reduction in scale allows more components to be packed into a given chip area, and so boosts the processing power of chips. In mechanical engineering, the sculpting of moving parts at scales that can only be seen under the microscope has led to devices such as sensors of pressure or vibration that are ever more sensitive. The components in these machines, which are called micro-electromechanical systems (MEMS) are now approaching the nanoscale, giving rise to nanoelectromechanical systems (NEMS).

Meanwhile, chemistry approaches the nanoscale from the other direction, as chemists become more adept, not only at making very large molecules, but also at assembling them into larger structures with specific functions, such as capturing light energy or performing catalysis. This discipline is loosely called nanochemistry.[49]

Size of Market to 2025

The global nanomaterials market is forecast to increase with a CAGR of 21% to $3.6bn in 2013 before reaching $100bn by 2025, with the medical imaging market predicted by one source to be responsible for 50 percent of the market.[50]

Barriers and Enablers

Barriers:
Health concerns/risks

Applications

Applications of nanomaterials that could arise over the next 10-15 years include displays, chemical catalysts, paints, textiles, lasers, cosmetics, water purifiers, land decontaminators, fuel cells and batteries, machine tools, anti-static packaging and diesel additives.

Institutions

- University of Aberdeen – Centre for Micro- and Nanomechanics
- University of Bath – nanomaterial synthesis, nanofluidics for LOC technology
- University of Bath – FP6 Novel Nano Templating Technologies (N2T2)
- University of Ulster – The Nanotechnology and Integrated BioEngineering Centre – diamond-like carbon, CNTs controlled growth, biomedical and biosensor applications
- Universities of Heriot-Watt, Glasgow and Strathclyde – quantum sensing
- EPSRC Nanotechnology Portfolio Centre, semiconductor and polymers, nanophotonics, self-assembly of nanomaterials
- Rice University, Centre for Biological and Environmental Nanotechnology
- Nanochem (Australia)
- Bureau De Recherches Geologiques Et Minieres – Carbon Capture and Storage using Nanomaterials
- ApNanoMaterials (US) and Weizmann Institute of Science (Israel), first commercial nano-lubricant
- ENSEMBLE FP-7, pattern formation in nanomaterials
- EUMINAFAB[51] – access to EU facilities for micro and nano fabrication

1.6 Nanotechnologies

Abstract

Nanotechnologies involve the manipulation of matter at a scale ranging from one to 100 nanometres. This is the level of individual molecules. At such scales the laws of physics operate in unfamiliar ways, and it is this that determines both the constraints and the opportunities of nanotechnologies.[52]

Summary

The scale at which we can manipulate and control matter has become ever smaller over the past several decades. The field of nanotechnologies utilises structures at the 1-100 nanometre scale, the scale of single atoms and molecules. At this scale materials often behave in a different wayfrom their macromolecular equivalents, for instance nano-sized aluminium is highly explosive, whereas the aluminium used in cans is relatively unreactive.[53]

Nanotechnologies, though diverse, share many common tools and techniques. There is also a strong degree of convergence between apparently unrelated fields at the nanoscale. For example, information technologies might interface neatly with biomedicine. That is one of the reasons why the potential for nanotechnologies to transform our lives is so large, and why these developments have implications for several of the other topics discussed in this paper.

Nanotechnologies may be constructed using either top-down or bottom-up approaches: carving nanostructures from bulk materials, or making them by the controlled assembly of atoms and molecules. The bottom-up approach is exemplified by the way that nature builds materials and 'devices', such as wood and bone or the light-harvesting structures called chloroplast in leaf cells. Indeed, some nanotechnologies have derived inspiration from natural systems, which can be mimicked in artificial nanostructures.[54]

The idea that nanotechnologies can enable other areas of science and technology is expressed in the concept of 'converging technologies': the combination of three broad areas – biotechnology, information and communications technologies (ICTs) and cognitive science – with nanotechnology could lead to radical new ideas and technologies.[55] [56]

It is difficult to predict the timescale at which nanotechnologies will become a reality. But it is likely that they will affect many areas of life. Potential applications and products of nanotechnologies include materials with improved properties – for example, harder, tougher, self-healing, non-wettable – more effective means of diagnosing diseases such as cancer, faster and more efficient computing devices and information technologies, and better ‘clean’ energy sources such as batteries and fuel cells.

In the short-term, 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 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. We may see the development of intelligent clothing that monitors the wearer’s blood pressure and heart rate, and detects dangerous chemicals in the environment.

Other potential longer-term applications include nano-engineered membranes to create more energy-efficient water purification processes, longer-lasting lubricants and higher performance engines.[57] For example, nanoscale porous membranes could dramatically improve the efficiency and reduce the size and energy consumption of water desalination plants. Nanoscale porous ceramic sponges can remove industrial contaminants such as mercury from waste streams. Nanoscale biofilters may be able to remove bacteria, viruses and prions. Nanoscale 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.[58]

The fact that the nanoscale is also the level on which much of biology ‘works’ – for example, in terms of transporting materials around cells or regulating the flow of material through membranes – also accounts for much of the potential impact of nanotechnologies on biomedicine. In effect, nanotechnology offers the possibility of intervening with biology at its natural scale, allowing such interventions to be far more effective and specific.

As with many technologies, the benefits that we could derive from nanotechnologies have possible risks attached. Nanotechnologies have become the focus of an intense recent debate about the responsibilities, ethics and social impact of emerging technologies. Some commentators have suggested that nanotechnologies present serious dangers, in terms of both intentional abuses and unintentional catastrophes.

There have been calls for careful consideration of the possible hazards before nanotechnological products become pervasive in our lives – although many such products are already in the marketplace. Others suggest that nanotechnologies present no *unprecedented* dangers – that the issues associated with introducing these new technologies are already anticipated and addressed by existing legislation, regulation and guidelines in, say, medicine and toxicology.

The status of nanotechnologies as a kind of ‘model new technology’ developing within the context of a public environment sensitised to these questions of risk and responsibility has proved to be instructive. So far, the debate seems to have settled quite quickly on what both scientists and pressure groups generally regard as genuine matters for discussion or concern, and to have dismissed some of the wilder and more alarmist notions that were raised when nanotechnologies first began to gain public attention. But these are still early days for the field, and the debate is only just beginning.

Size of Market to 2025

Global market in nano-enabled products is expected to grow from $2.3bn in 2007 to $81bn in 2015.[59]

Trends

Nanotechnology has seen a dramatic expansion in the past decade. Research indicates that private funding for nanotechnology reached $9.6 billion in 2008, while government investment was $8.6 billion. This was the first year that private spending exceeded public spending. Global nanotechnology revenue in 2007 was £2.3bn, predicted to rise to £81bn by 2015, with ICT, automotive and consumer goods the three largest sectors.[60]

The UK has a world-class reputation in nanotechnologies research with a strong research base.[61] There were over 600 nanotechnology companies in the UK in 2009.

Some sectors have invested heavily in nanotechnology. For example, over the past eight years there has been a 170% increase in the size of the nanotechnology sector in chemistry.[62] Chemical firms make up 52% of companies in the field, followed closely by the electronics/physics sector with 34% of the total.

The European Commission is currently implementing a programme to invest almost €5 billion across Europe in nanotechnology research for the period from 2007 to 2013.[63]

Barriers and Enablers

Barriers

- Although fears about the more extreme 'science fiction' applications of nanotechnologies (e.g. nanobots, 'grey goo') appear to be receding, there are concerns about the health, safety and environmental impacts of free nanoparticles and nanotubes, which are already finding some applications, e.g. as zinc oxide nanoparticles in sun-cream and anti-microbial wound dressings containing nanocrystalline silver in the US.
- Limitations in metrology, of, for example, length and force, may slow the development of tools, standards and calibration techniques which are essential if appropriate legal requirements for health, safety and performance are to be set. The need to define and implement testing and validation procedures, which themselves may take years to conduct, is likely to limit the rate of uptake, particularly in the medical field.
- Commercialisation
- Knowledge Transfer
- Fragmented Industry
- Skills
- Public perception
- Regulation

UK capability

The UK has the third highest number or nanotechnologies companies in the world after US and Germany.[64]
Strengths in nano-optics (3rd after US and Japan) and nanoscale material (4th after US, Japan and Germany).[65]
Fourth largest number of nanotechnologies patents applied for globally.
Strength in nanotechnologies standards – British Standards Institution (BSI).[66]
UK has world class reputation in research.[67]

1.7 Intelligent Polymers (‘plastic electronics’)

Abstract

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, which 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.

Summary

Key technologies

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 electric current. Artificial muscle may replace electric motors in some 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 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 about since the 1930s, but research on shape-memory polymers since the 1980s has shown the latter to have greater manipulability and ease of production than equivalent alloys. These polymers can revert back to an original shape when exposed to heat or to ultraviolet radiation, for example.[68]

Organic Light Emitting Diodes (OLEDs), Polymers (OLEPs): in the field of lighting, interest has been sparked around displays based on organic polymer LEDs (OLEDs). These large area devices are relatively inexpensive to manufacture, are efficient and can emit light from the near UV to the near infrared. Furthermore, they can be made extremely flexible.[69] **Wide-band gap semiconductors** e.g. gallium nitride (GaN) may be one technology to enable their application.

Size of Market to 2025

The Council for Science and Technology (CST) has cited forecasts that the plastic electronics market will be worth £12 billion by 2011, £15-£30 billion by 2015 and £100-£250 billion by 2020-2025. It has also argued that the value to the UK is most likely to be in materials, the designs of devices and structures and process knowledge.

The Technology Strategy Board predicts the global market will rise from $2bn in 2009 to $330bn in 2027.

Disruptive Potential

Plastic electronics is an enabling technology for three key markets: lighting, photovoltaics and integrated smart systems. The introduction of new low-cost, flexible molecular and macromolecular materials, encompassing polymers, advanced liquid crystals and nanostructures, and including carbon and silicon nanowires, is predicted to have a disruptive impact on current technologies. Not only do they offer cost/performance advantages, they can also be manufactured in more flexible ways. They will provide more functionality and be ‘engineered’ for a wider range of applications.

Trends

The UK company Plastic Logic released its first commercial product, the QUE eReader in January 2010. Increased levels of investment both in the UK and worldwide, e.g. TSB call for Plastic Electronic applications.
Plastic transistors have recently overtaken amorphous silicon transistors in terms of performance.
Energy – small organic molecules and plastic semiconductors could enable the development of organic solar cells with broader applications, increased efficiency and reduced cost.
Digital and Networks – flexible displays will enable a new range of cheap personal devices.

Applications

Existing markets for OLEDs include electronic paper, advertising posters and use in mobile phones and other handsets. Other applications that are likely to emerge over the next five years include RFID tags and smart sensors, retail signage and lighting. It is anticipated that within seven years, samples of full-colour video-capable displays printed on flexible substrates will be available, with consumer electronic devices and large digital signage moving into high volume production. Plastic electronic technology can also be incorporated onto clothing for use with mobile computing, smart interactive textiles and intelligent tags.

UK capability

The UK is a world leader in plastic electronics but with strong competition from the US, Japan and Germany. Holland and Germany are increasing their investment. UK expertise is strong with significant commercial presence in companies such as Plastic Logic. The UK also has significant research expertise and knowledge, including low-cost manufacturing and printable electronics.

1.8 *Active Packaging*

Abstract

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 RFID into packaging also enables smart monitoring with implications for supply chain management and logistics. Key markets for active packaging include the food and pharmaceutical industries, where a number of technologies have already been commercialised.

Summary

In the food and pharmaceutical industries, technologies are being developed to extend and monitor the shelf-life of foods and drugs. Thermochromic pigments, which change when exposed to heat, can be used to develop packaging materials that can indicate what has happened to the contents and hence to determine the likely shelf-life of food. Similarly, the presence of pathogens can be monitored using materials, or sensor technology, as well as chemicals that are produced as food perishes. A future application of this kind of technology includes packaging that can recognise markers of genetic modification, for both monitoring and tracking GM food.

Other technologies can be utilised actively to modify the atmosphere surrounding the food or drug. For instance, oxygen scavenging materials are used in the dairy industry to preserve cheese and milk products, without the need for additives,[70] while anti-microbial packaging has been developed to combat certain bacteria, although new compounds will improve effectiveness.[71] Additional technologies include compounds that can selectively exchange gases, control temperature, including self-heating or cooling coatings, and control moisture. For instance, the US Army has developed flexible plastic packs that can absorb clean water from dirty puddles by forward osmosis, to rehydrate dried food. The technology has additional uses for potable water, something that should be useful in the third world, particularly in the preparation of medicine during emergencies.

Photovoltaic, photochromic, piezochromic and hydrochromic materials could add functionality to packaging. These materials could be applied as inks during the printing and decoration of packaging.

Integrating active packaging with sensor technology, for instance RFID or similar devices, has already had an impact on logistics and supply chain operations.[72] For instance, the use of RFID has improved the capability of supermarkets and other suppliers to monitor stock, from production to the shop-floor. When coupled with sophisticated data analysis and modelling techniques, supermarkets can optimise their supply chain to ensure that the right quantities of goods are produced, distributed and in store at any given time, thereby optimising delivery networks and minimising waste.

In hospitals, RFID could be used to minimise medical errors. A 2004 report estimated that medical errors were directly responsible for 40,000 deaths a year,[73] and estimates of preventable medical errors in the United States suggest they cost $17bn a year. In the UK, unclear packaging and labelling is a contributing factor in 25 per cent of reported medication errors in the UK. Further applications in healthcare include the use of integrated sensors and actuators to warn for non-compliance with prescription advice, and to prompt or warn users, for instance using vocal or printed moving displays.[74] The integration of voice or Braille devices would also have direct benefits for visually-impaired users.

Active packaging technologies are also being applied to combat counterfeiting. VTT Research in Finland is integrating printed organic RFID tags with mobile sensor technology to allow goods to be scanned at point-of-sale to determine authenticity.[75]

Trends

Demand for active packaging in the US is set to reach $1.9 billion in 2013. New generations of products and more cost competition will spur greater market acceptance for many product types.

Food and beverages are the largest markets for active packaging, accounting for over 50% of demand in 2008.

Suppliers face demands for longer shelf-life for processed foods and packaged fresh foods. They are also under pressure from consumers and retailers to improve food safety and to reduce losses caused by oxidation and poor temperature control in the supply chain.[76]

Size of Market to 2025

Global market has been estimated at $3.5bn in 2014, with a CAGR of 7% between 2009 and 2014.[77]

Barriers and Enablers

Barriers:
Relatively high cost, consumer resistance and restrictions imposed by food safety legislation, particularly in the EU.

Enablers:
Reduce environmental impact of packaging.

UK capability

The UK is considered a leader in active packaging.[78] The biggest technological challenges are to increase the range of smart tags, and to reduce dramatically their price so that they become as disposable as today's barcodes. The goal is to devise labelling devices based on a common standard that can operate across the supply chain, and eventually be linked to the internet.

EPSRC supports grants of approximately £1m/yr with clusters of expertise at Sheffield, Bath and Manchester.[79] Other Government support includes the 'SMART mat' node of the Materials KTN.

Supermarkets in the UK lead Europe in sophistication, product range and quality. UK households are ahead of the rest of Europe in making online purchases. A coherent programme to develop smart label and packaging could consolidate and extend this lead, with commercial benefits.

However, Europe lags the US and Japan in smart packaging. Major companies such as Proctor & Gamble fund research at the Auto-ID centre at MIT.

Opportunities exist to print electronic devices, e.g. at PETEC – there is a need to build on UK strengths to create supply chain value – opportunities need to be understood and points of leverage identified.

1.9 Smart (Multifunctional) and Biomimetic Materials

Abstract

Smart – or multifunctional – materials are ‘designer’ materials which interact with their environment to carry out a range of tasks. Applications include materials that self-repair, sunglasses that darken on exposure to light and engines that sense trouble before they breakdown. 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.

Summary

Smart materials inhabit a highly interactive ‘technology space’, which also includes the areas of sensors and actuators, together with other generic platform technologies such as nanotechnology. 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.

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 shape-memory polymers which form different structures when exposed to varying stimuli, such as heat or light.

Smart materials have a rangeof applications across fields from construction, medicine and electronics. For instance, shape-memory polymers (see Section 1.7)havebeen used to create stents that expand on exposure to body heat to open up arteries. In electronics, technologies have been developed for the activedisassemblyof electronic waste, with environmental benefits. Shape-memory polymers also enable self-repair, for instance to fix damage to a car bonnet on heat exposure.

Skin is a good example of a naturally occurring smart material. It senses the sunlight and changes pigmentation in response, thereby signalling that tanning or burning is occurring. In fact, most biological materials are smart in some sense.

This is why organic templates could be important both for designing and manufacturing smart materials in the future.

Biomimetic materials

Biomimetic refers to human-made processes, substances, devices or systems that imitate nature. The aim is to understand how nature produces a useful structure or function and then reproduce it artificially. The underpinning idea is that evolution has caused plants and animals to become highly efficient – well-known examples include the structures of sea-shells, the skin of dolphins for boat hulls, and water-repellent paint based upon the surface of lotus flowers which consists of tiny pyramidal wax particles. Polymer-based solar cells inspired by photosynthesis in plants are another example. Interdisciplinary approaches are demanded to understand and then exploit such properties.

Military scientists are attempting to recreate the properties of the Grey Birchir – an African freshwater fish – to produce a material that can withstand penetrating impacts, 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. Imitating how a scab stops bleeding, a hardening epoxy resin is released from embedded capsules to seal cracks and restore the plane's structural integrity. Researchers are also working with a manufacturer of aerospace composites to develop a system where the healing agent moves around the plane as part of an integrated network. There are, however, concerns about the weight and cost of these technologies.

Biomimetic technology has also been successfully applied to architecture, robotics, medicine and the environment.

Applications

The key to these future smart materials is our growing understanding of, and ability to manipulate the world at the molecular level. Understanding how molecules cross membranes could enablethe design of materials that function as 'delivery platforms'. For example, a T-shirt could deliver vitamins through the skin over an eight-hour period. Alternatively, a biofilter could protect a water or air supply from bacteria.

Smart materials could also incorporate sensors, silicon-based or organic. This could, for example, lead to the development of paints with millions of tiny sensors that respond to the environment and communicate with each other to strengthen their insulating capacity in very cold or humid weather. Another application would be ink-jet fluids with organic molecules that respond to electrical signals, forming the basis for flexible displays. Structural health monitoringis another area of impact for smart materials and sensors. Embedded sensors are currently used to monitor stress and damage to bridges, thereby reducing repair costs and enabling preventative monitoring. Such applications could be extended, for example to the monitoring of engines.

Smart materials may also be a source of **structural power** using functional materials that are both structural and capable of generating or storing power. Supported by an EU grant, Imperial College is working with Saab to develop a car body material for a hybrid car. The material could also be used for mobile phone and laptop cases to avoid the need for parasitic batteries. Spall liners for armoured vehicles or aircraft skins could power future weapons such as laser or microwave energy weapons.

Smart and interactive textiles (SMIT, see Section 1.10) can sense electrical, thermal, chemical, magnetic or other stimuli in the environment and can adapt or respond to them, using functionalities integrated into the textile's structure.

Trends

Swifter development and application of European standards in the global market, combined with appropriate measures for the protection of intellectual property, e.g. through support for SMEs, could increase the supply of protective textiles. Coordinated public procurement policy could also play an important role.

Institutions and Applications

Imperial College –wing morphing technology, recently seen a successful demonstrator tested in a wind tunnel.
Imperial College – working with Saab to develop a car body material for a hybrid car.
NPL – functional materials
QinetiQ
TeamMast (QinetiQ-BAE Systems)
Univeristy of Bath – piezoelectric fibres, morphing composites

University of Bristol – morphing technology which is being assessed by wind turbine blade manufacturers and the aerospace industry.
University of Bristol – mimicking the healing processes found in nature to create aircraft that mend themselves automatically during flight.
Univeristy of Leeds – piezoelectrics

The US has developed a demonstrator aircraft (Polecat) in which the flight controls are operated by wing morphing – it has no discrete flying control surfaces like flaps and aileron.

Polarised biomaterials have been developed that mimic the piezoelectric behaviour of bone (FP7 Bioelectric surface).[80]

1.10 *Smart Interactive Textiles*

Abstract

Smart and interactive textiles (SMIT) 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 work with their own control and response mechanism.[81] SMITs are usually dependent on stimuli-responsive polymers and/or integration of sensor and communications technologies.

Summary

To date, the US – particularly the military, but also NASA – has lead the development of SMIT and applications for such areas as body armour, artificial muscles,[82] 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 (FP6) 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.[83] A new project, Heartcycle, aims to take this further in FP7 to allow information to be shared both with the user and with health practitioners.[84]

Similarly, techniques are being developed to monitor lung-fluid using bio-impedance measurements, and ECG and respiratory monitoring during sleep using 'Smart Beds',[85] while alternative SMIT technologies are being developed for drug delivery, such as reconfigurable fabrics,[86] diagnostics and biosensing. Recently, a brain implant composed of water-soluble silk was designed to melt away to leave electrodes in direct contact with brain tissue.[87]

Technologies are also being developed drawing on technology from other sectors. For instance, textile-based solar panels, devices for energy scavenging and flat-film batteries are being incorporated into textiles for a range of applications,

including embedded microcomputers and displays. Biodegradable textiles are being developed for the delivery of feedstocks and pesticides in agriculture.

Optoelectronic textiles offer cost and weight savings in electronic devices, although performance is lower than that of traditional electronic devices.[88] Radar-absorbing electronic fabrics have been developed which could be used to overcome radar issues caused by wind turbines, as well as for military applications.

The fashion industry is also a potential key market for SMITS. Philips has developed technology that integrates LEDs into fabrics, while researchers have developed ‘second skin’ that acts as an emotional layer to deliver mood-responsive aromas and pheromones.[89] 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.

Size of Market to 2025

The US market for SMIT, $70.9 million in 2006, is expected to rise at an average annual growth rate of approximately 40% to $391.7 million in 2012, with rapid growth in military, biomedical and vehicle safety and comfort applications.

Sales of conductive fabric products are expected to more than double each year until 2012.[90]

Swifter development and application of European standards in the global market, combined with appropriate measures for the protection of intellectual property could increase the supply of protective textiles.

UK capability

Some in defence research.

Peratech[91]– for clothing with sensors; integrated pressure sensors for ipod, iphone etc.

Institutions and Applications

- Myheart EU FP6 project – solutions for functional clothes with integrated textile sensors

- Sensatex – T-shirt that acquires physiological information and movement data from the human body
- SmartLife® Technology – healthvest – knitted sensors
- Biotex – EU FP7 project focused on physiological sensing, developed oxygen probe
- Systex – EU project to develop an extensive and detailed roadmap of current and possible future technological barriers to smart textiles
- Philips – range of physiological monitoring devices, e.g. smart bed

Energy and low carbon technologies

2.1 *Advanced Battery Technologies*

Abstract

Advanced battery technologies aim to develop modern alternatives to the traditional lead-acid battery, such as lithium-ion. Advanced batteries could replace fossil fuels in transport, cutting CO_2 emissions, if electricity from low-carbon sources can 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.

Summary

There have been many advances in battery materials in recent years. A key driver of investment has been batteries for hybrid cars and the need to store energy from variable-output renewable energy sources.

Large-scale storage techniques are thought to be a key technology for the integration of renewable and intermittent energy sources into the national grid. Flexible and scalable storage would allow short-term supply and demand to be balanced in local, national and international grids. The only current economic technology for long-term energy storage is pumped hydroelectricity.

Utility companies are starting to look at sodium sulphur (NaS) batteries. These are long-life (15 years) room-size batteries that can act as local reservoirs of electricity, perhaps in combination with renewable generation. A recent project deployed a battery with 1.2 MW capacity. Other potential battery technologies include all-liquid batteries which can operate at lower costs and have a greater lifetime than existing technologies and, crucially, can operate at much greater currents than existing stock allowing large amounts of electricity to be absorbed.[92] Similarly, low-cost gravel batteries are under development in the UK. These utilise spare electricity to heat and pressurise Argon which is then allowed to cool, heating up gravel in one of two silos to 500^{o}C. The gas then enters the second silo where it expands, cooling the gravel in the second silo to -160^{o}C. Energy is stored as the temperature difference between the two silos. To release the energy the cycle is reversed. This technique utilises low cost components, with the advantage of occupying around 1/300th of the land required for existing storage by pumped hydroelectricity.[93]

Small-scale storage is dominated by the battery industry. A range of new technologies to replace existing stock is under development including thin-film batteries which, although currently very expensive to produce, have a long storage time and are solid state. Their ability to retain charge over long periods of time makes them suitable for applications that require only small amounts of electricity over a long period of time.

MIT has researched a new material: lithium nickel manganese oxide. This would be suitable for small devices and can discharge and recharge in 10 minutes. MIT has also looked into coating conventional lithium-ion batteries with lithium phosphate which greatly shortens the recharging time.

Nanotechnology is also set to have a large impact on batteries. A team at Stanford University embedded a silicon nanowire electrode into a lithium battery, tripling its capacity. Lithium-Air batteries are also benefiting from nanotechnology advances. Novel catalysts have been developed that offer greater efficiency and longer lifetimes, the two key factors that currently prevent commercialisation of these batteries. Lithium-air batteries are of interest as they have a large energy storage potential, for instance to extend the range of electric vehicles.[94]

Many emerging technologies that have yet to come to market could revolutionise battery usage through step-changes in capacity and recharge times.

Size of Market to 2025

The most significant products of advanced battery technologies are in transport and in energy storage systems. Current world markets for batteries have been estimated at $50bn with predicted growth rates of 7-30% per annum.[95]

UK capability

The UK is strong in battery technologies, for example, the ‘Flow Battery’ from Plurion and the lithium-sulphide battery developed by Oxis. The university base includes Cambridge, Imperial, Newcastle, Manchester, St Andrews and Strathclyde. Some commercial development work exists. The TSB launched an Innovation Platform in low-carbon vehicles in May 2007.

The UK may benefit from being at the forefront of developing and demonstrating the practical application of this technology, with some manufacturing capability. Larger markets will probably be developed through international partnering.

The gravel battery is a UK invention developed by a Cambridge-based company, Isentropic.[96] The TSB recently supported the company in its ‘Clean and Cool’ Trade Mission to the US.

The battery maker Atraverda[97]uses a conductiveceramic (Ebonex) to produce higher performance batteries.

2.2 Bioenergy

Abstract

Bioenergy encompasses all energy derived from biological organisms. The use of bioenergy is not a new phenomenon, for instance, bioenergy utilisation through burning of plant material. 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.

Summary

A typical bioenergy process chain involves production of biomass, transportation, storage and pre-treatment, before conversion to produce the final energy, biofuel or chemical feedstock. Typical process technology for biomass includes solid fuel conversion, liquifaction, gasification and pyrolysis and biodigestion (anaerobic digestion). Additional uses for biomass include heating, power and fuel for transport.

The advantages/disadvantages of bioenergy need to be assessed across the whole process chain. This approach is especially relevant when calculating carbon emissions.

Most research on bioenergy focuses on the use of biofuels. Biofuels in use today are often categorised as first, second or third generation biofuels. First generation biofuels include biodiesel, which is currently produced by esterification of oil-rich crops, such as rapeseed, and bioethanol which is produced commercially from the fermentation of sugar and hydrolysis of starch crops, such as sugar cane, corn, sugar beet and wheat.[98] Additional technologies include the production of ETBE from biomass for use in the production of gasoline from crude oil, generation of biogas and straight chain vegetable oils.

Second generation biofuels were developed to counter limitations with first generation biofuels which are thought to have a threshold above which they become unsustainable with regards to food supply (i.e. competing for land with food crops) and biodiversity and emissions, and price competition with existing fuels. The circumstances of sustainability are highly case specific to the crop involved and the location and manner of its production, combined with wider life-cycle assessment.

Second generation biofuels typically use lingo-cellulosic biomass. Technologies include Biomass to Liquid, lingo-cellulosic biomass, bio-DME/Methanol, Biosynthetic Natural Gas, Bio-oil/Bio-crude, Hydrocarbons from catalysis of plant sugars, Biohydrogen, Bioelectricity/CHP, Biobutanol.

Production of biofuels from ligno-cellulosic biomass is at the pilot stage, although demonstration projects are underway. Biorefineries are some way behind ligno-cellulosic biofuel production and are unlikely to be fully demonstrated before 2015 (see section 3.3 Industrial biotechnology). Only approximate figures for ligno-cellulosic biofuel production can be given in the absence of large-scale demonstration performance data. With the exception of biomass co-firing in fossil power plants and biogas production from agricultural residues, all other technologies still require considerable research and development.

Third-generation biofuels are centred round the use of algae. Algae have been demonstrated to be one of the most important potential future sources of biomass. Microalgae are single-cell, plant-like organisms that use photosynthesis and convert carbon dioxide (CO_2) into biomass. From this biomass, both potential resources and active substances, as well as fuels like biodiesel, may be produced. When grown in photobioreactors (rather than open ponds), algae take up the amount of CO_2 that is later released again when they are used for energy production. Hence, energy from algae could potentially be produced in a CO_2-neutral manner.

The application of CCS technologies to biofuels brings the potential for negative emissions to be achieved.

The running costs and design of the photobioreactors necessary for algae cultivation are barriers to their use in energy production.

Trends

There are seven operational biomass plants in the UK, with an additional nine approved, and at least another 31 in planning or proposed for development.[99]

The European Industrial Initiative (EII) proposes to carry out an ambitious demonstration programme of different bio-energy pathways at a scale appropriate to the level of their maturity – pilot plants, pre-commercial demonstration or full industrial scale. Up to about 40 such plants would be built and operated across Europe to take full account of differing geographical and climate conditions and logistical constraints.

A longer term research programme is intended to support the bio-energy industry's development beyond 2020. The cost of such a European programme is estimated at €8.5 billion over the next 10 years.[100] Recently the Pentagon in the US has developed low-cost algal fuels, which they expect to bring to commercial viability by the end of 2010.[101]

Barriers and Enablers

Enablers:
Energy independence and security
Environmental sustainability
Legislation including EU target for renewables as part of the EU's Renewable Energy Directive.

Barriers:

'Fuel users' need to bid for waste derived fuels from Local Authorities under OJEU procurement rules, but, apart from large power generators, few Renewable Energy developers have either the skill or the financial resource to do this.

The need to build robust fuel chains with strong, financially creditworthy, counterparties. Waste-derived fuels potentially enjoy such status, given the 25-year MSW supply contracts from Local Authorities to waste contractors operating Mechanical Biological Treatment (MBT) plants from which Solid Refuse-derived Fuel (SRF) is derived. However, much waste-derived material will be < 90% biomass. To complete the fuel chain loop requires creditworthy SRF users capable of commanding bank support for the fuel use.

Land use availability.

UK capability

In 2007 the EU waste sector provided 11TWh energy from waste, 18 TWh from landfill gas and 2.5TWh from sewage gas. Estimates of future availability of biomass resources vary with a mean global potential of 55,000 – 111,000 TWh.[102] UK market share estimate = 70TWh of liquid transport fuels.[103]

The UK total energy requirement in 2020 is estimated to be 1800TWh, of which 263TWh will be supplied by Renewable Energy, of which 100TWh will be contributed by biomass, of which approximately half (56TWh) will be derived from waste.[104]

Institutions

Drax – co-firing power plants

Sustainable Bioenergy Centre

UK University of York, Carbon Trust

BBSCR and Cambridge – Sugars as a fuel source

UK Edinburgh Napier University

Hong Kong Bio

National Non-Food Crops Centre

2.3 *Carbon Capture and Storage*

Abstract

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.[105] CCS technologies may allow fossil fuels to remain major components of power generation despite the demand for low-carbon electricity generation.

Summary

The UK was reliant on fossil fuels for approximately 70% of its electricity generation in 2008,[106] with 31% and 24% of generation from gas and coal respectively. Whilst renewable energy will be a key component of the future UK energy mix, fossil fuels will remain a major component of future energy supply in the 2020s and beyond, especially if ageing nuclear plants are not replaced by new nuclear technologies.

Rather than a single technology, CCS covers a series of technologies enabling the capture of CO_2 from fossil fuels, 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 mature, **post-combustion capture**, or ‘scrubbing’, is routinely used for flue gas separation in the petrochemicals industry and urea manufacture. Post-combustion is of interest to the UK as the technologies can be retro-fitted 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 post-combustion approaches.[107] Two main technologies are under development in Europe.

The second 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 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 which 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, 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 is required.[108] The German SchwarzePumpe plant is a leading demonstrator of oxyfuel capture. In the UK, the Government is also supporting the demonstration of a commercial scale (40MWth) oxyfuel burner at the Doosan Babcock test rig in Renfrew, Scotland.

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 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 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.

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

Size of Market to 2025

The UK will provide £1bn funding of CCS over the period 2011-2015; there is a world market of £150bn.[109] Most developed and developing countries are currently dependent on fossil-fuels for energy generation; for instance, half the US supply is from fossil fuels.[110] CCS technologies have both a domestic and export market, with value in engineering, particularly in systems integration knowledge. Effective market incentives, and perhaps carbon pricing, may be necessary for widespread adoption of CCS technology.

The value to the UK from global markets for new advanced coal-fired power generation plant, including that fitted or retrofitted with CCS, is estimated by the AEA at £1-£2 bn/yr by 2020 and £2-£4 bn/yr by 2030. This equates to £20-£40 bn in total between 2010 and 2030. This level of activity would sustain a total of about 30,000-60,000 jobs in the UK in 2030.[111]

Disruptive Potential

Advances in CCS technology could result in high efficiency, low-cost and low-carbon CCS power plants. In particular, high-efficiency post-combustion technologies would extend the life of existing power plants and reduce the urgency of moving towards renewable energy. Successful post-combustion technologies can also be utilised on many industrial major plants. Real disruption would occur if CCS technology can be miniaturised, with capture technologies fitted to domestic sources of CO_2 from cars through to fridges.

Trends

The 2009 budget announced support for four demonstration projects for CCS on power plants, and up to £90 million to fund detailed preparatory studies for the first such demonstration project competition.
On 19 October 2010, the UK Government announced up to £1bn in capital funding for the first demonstration project competition – the largest confirmed commitment to a single commercial-scale CCS project in the world to date. The Energy Act 2010 provides a statutory framework for a levy to be charged on electricity suppliers to support CCS demonstration projects. In the Spending Review in October 2010 the Government committed up to £1 billion that will be invested in one of the world's first commercial scale carbon capture and storage (CCS) demonstrations on electricity generating plant. This is the world's largest public funding contribution to a CCS project. However, this funding is provided from general public spending and so does not require the introduction of the levy. The Government will take a decision on whether to introduce such a levy or fund future demonstrations from general public spending once work is completed in Spring 2011 on the reform of the Climate Change Levy to provide support to the carbon price. The Government plans to publish this consultation in November 2010. The EU has also funded CCS demonstration projects. For instance the New Entrant Reserve (NER300) is expected to support up to 12 commercial-scale CCS demonstration projects, encompassing pre-combustion, post-combustion, oxyfuel and industrial applications.[112]

Barriers and Enablers

Barriers:
Cost of carbon
Infrastructure
Current lack of clear regulatory regime (including allocation of liabilities)

Enablers:
Increased energy demand
UK's existing position as home to a major hydrocarbon industry providing infrastructure and skills

Applications

CCS applications include retro-fitting of power stations, and industrial plants.

UK capability

The UK has a strong knowledge and capability in CCS technology. Whilst not considered a world leader, the UK has strong capabilities in systems integration, design and engineering and has some of the most advanced plans for CCS demonstrators. There is also opportunity for the UK to develop and export CCS technology. The North Sea is also a key potential storage resource.

Institutions

Leading university research centres include Imperial College, Cranfield University (CO_2 capture), Edinburgh, Heriot-Watt (geological storage), Nottingham, Cambridge, the Tyndall Centre and Plymouth Marine Laboratory.

Other non-commercial UK centres of expertise are the British Geological Survey (BGS) and the IEA Greenhouse Gas Programme. Fourteen Universities and BGS have come together to form the Carbon Capture Storage Consortium to coordinate CCS activities in the UK.

The commercial sector is actively pursuing research, demonstration and commercial deployment of CCS. Key players include BP, Shell, Eon UK, Scottish Power, Scottish and Southern Energy, Air Products, Alstom UK, Doosan Babcock and Schlumberger. Industry has proposed at least eight large-scale demonstration projects in the UK for power generation with CCS, all of which are currently in the study/evaluation phase.[113]

2.4 Nuclear Fission

Abstract

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 Government or the public, including cost, safety, regulation, proliferation and waste disposal, which may continue to hinder uptake in the UK.

Summary

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.

Most new-build nuclear plants are generation III technologies, with standardised design to reduce cost, and expedite licensing and construction times; give higher availability and longer operating life; higher burn-up to reduce fuel use and waste; and increased safety notably with passive/inherent safety features. Current reactor units can produce over 1600MWe.

There are four main types of generation III reactors: light-water reactors – including advanced boiling water reactors and advanced pressure water reactors (PWR) – heavy-water reactors, high-temperature gas-cooled reactors (HTRs) and fast neutron reactors (FNRs).

Fourth-generation technologies are now under development. The Generation IV International Forum (GIF), an international taskforce, led by the USA and involving 12 other countries including China, France and Euratom, is pursuing six clean technologies selected on cost, safety, sustainability: gas-cooled and lead-cooled fast reactors, molten salt reactors (MSRs) (two types), 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 on Gen IV both directly, as part of international consortia,

and through Euratom. 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 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 cogenerate 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 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 considered in the future. This will also be the case for fuel for Generation III plants. There are challenges of 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. Research is needed in areas such as:

- characterisation of legacy materials including site, plant and inventory
- understanding the behaviour of waste during retrieval, handling and pre-treatment
- retrieval and remote deployment technologies
- decontamination technologies
- technologies to quantify and remediate contaminated land
- development of Orphan Waste Treatment technologies.

In addition to large nuclear fission plants, there is also interest in small <500MWe systems, that can deliver reduced capital costs, and independence from large-grid systems. These small systems involve a wide range of technologies. Projects are underway in China, South Africa, USA, Siberia and India, based on PWR, HTR, Liquid-metal Reactor and MSR technology.

Size of Market to 2025

UK market: £50bn in 2023
2020 – £16bn in clean up – £55bn in reactor support – £18bn in new build.[114]

Trends

Nuclear reactors have been operational in the UK since 1956. The UK currently has 19 reactors generating up to one fifth of its electricity. Eighteen of these are planned to be retired by 2023.[115]

Whilst UK policy has been generally supportive of nuclear power, issues over cost, regulation and licensing, and investment have curtailed uptake of nuclear energy in the UK. This is coupled to public and Government concerns over the safety and reliability of nuclear power, over reactor meltdowns, the safe disposal of waste and environmental/health impact. Public attitudes remain an important factor in determining the successful exploitation, or otherwise, of this technology.

In 2006, concerns over energy security and carbon emissions reinvigorated support for nuclear power, and spurred proposals to address barriers to nuclear build, including new design certification (HSE, 2006), and stream-lining approval for major projects (UK Planning Review, 2007).

In 2008, Government released the Nuclear White Paper 2008: 'Meeting the Energy Challenge'.[116] The paper highlighted the need for 30-35GW of new electricity by 2030, and the need for two-thirds of the investment to be made by 2020, as it takes a long time to plan and build nuclear power stations.

Current UK plants are first- or second-generation. Replacement with third-generation plants is currently underway, with 10 sites proposed for development. The HSE is currently assessing two third-generation reactor designs, the UK-EPR (Areva and EDF) and the AP1000 (Westinghouse).

Barriers and Enablers

Barriers:
Key barriers to the future of the global nuclear industry include relative financial and carbon economies compared to alternative fuels, Government subsidy, skills and research development, nuclear waste disposal and infrastructure capability.[117]

For several years, a lack of investment and commitment to fission research (for example, the withdrawal of Generation IV funding by UK Government) has resulted in the UK losing its profile and market position in several key topics, e.g. fuel and reactor design work, reactor physics, thermal hydraulics. However, UK companies continue to access EU programmes, albeit at a relatively low level. EU programmes such as EURATOM are set to continue to part fund EU research activities and the challenge remains for UK companies and organisations to become significantly involved, e.g. through finding sufficient leverage funding.

Enablers:
The UK has the newest and potentially the most capable research facilities for handling radioactive material at the National Nuclear Laboratory.

UK capability

UK has strong research and development skills; however,the majority of UK nuclear power stations are operated by foreign companies. There are a few smaller UK companies with expertise in manufacturing particular nuclear components; however, national manufacturing is not currently geared up to build new power stations.

Given the expected growth of the civil nuclear industry within the UK over the coming decades, combined with the Nuclear Decommissioning Authority (NDA)'s clean-up goals, it will be important to safeguard and expand existing nuclear skills.

Institutions

GIF
Euratom
Oxford Future Energy
Sheffield Nuclear FiRST DTC
Nuclear Industry Association

In addition, the UK's National Nuclear Laboratory (NNL) is a leading nuclear science and technology services provider specialising in a number of key areas:

- Nuclear Science
- Waste and Residue Management
- Plant Process Support

- Modelling and Simulation
- Materials and Corrosion
- Environmental Management
- Homeland Security and Non-Proliferation
- Specialist Analytical Services
- Knowledge, Data and Laboratory Management.

2.5 Fuel Cells

Abstract

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 to 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.

Summary

The fuel choice depends on the application and the type of fuel cell. Fuels include hydrogen, methanol, ethanol, natural gas, LPG, bio-gas, diesel and gasoline.

Fuel cell R&D is a multi-disciplinary field, encompassing issues such as material science and engineering, catalysis, electrochemistry, thermal fluids, system design, integration and control, and power conversion.[118]

Traditionally, three main fuel cell types have been the focus of UK research: alkaline, polymer and solid oxide, with the polymer and solid-oxide 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 using methanol fuel.

The hydrogen fuel cell vehicle market, although less mature than electric vehicles (itself not mature), 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 (SOFC) systems may offer a solution. The cost remains prohibitive for general take-up, 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 the development of energy infrastructure as grids move towards renewables and microgeneration and, potentially, towards a hydrogen economy.

Size of Market to 2025

Global market 2009 = $8.8m 2014 = $14,000 CAGR: 9.6% according to iRAP report.

The global fuel cell market could be worth over $26bn in 2020 and over $180bn in 2050. The UK share of this market could be $1bn in 2020 rising to $19bn in 2050. In recent years the fuel cell sector has continued to grow, despite the global economic downturn; experiencing a 41% increase in shipments in 2009 relative to 2008.[119] Over 100 UK companies are involved in the global fuel cell industry.[120]

Applications

Fuel cells are being developed for a wide range of applications, ranging from a few Watts for battery replacement for consumer goods such as laptops and mobile phones, 100 Watts for small generator replacement, kWs for micro-combined heat and power (CHP) or auxiliary power units, 10 kWs for fuel cell engines, to 100 kWs or MWs for industrial cogeneration of electricity and heat.

UK capability

Materials and catalysts technologies for fuel cells and reformers have been developed by Johnson Matthey for 30 years and Rolls-Royce has been developing SOFC stacks for over 10 years. However, most companies in the sector are small.

UK strengths include SOFCs (Rolls-Royce, Fuel Cell Systems + components e.g. Precision Micro) PEMFCs (Intelligent UK is an international player, Johnson Matthey world-class in components and membrane design) and DMFCs (CMR fuel cells, and Johnson Matthey and IneosChlor supply components worldwide). Ceres Power Ltd for micro-Combined Heat and Power (CHP) systems.

The UK has a strong base of internationally competitive firms developing reformer systems technology. However, the UK owns only 80 of 5000 global patents in fuel cell technology.

Institutions

The UK has pockets of world technology leadership in fuel cells, particularly in fundamental and applied/industrial research.[121] There is, however, limited involvement in emerging commercial markets.

There are a number of industrial research activities – mainly being carried out by SMEs, including Ceres Power, CMR fuel cells, Intelligent Energy – with the potential to develop innovative products, based on defensible intellectual property, in a five-year timescale. There are also major companies (not all UK) – including Siemens/Westinghouse, Rolls-Royce, Mitsubishi and United Technologies – carrying out R&D into fuel cells for power generation. The TSB's Innovation Platform in low-carbon vehicles supports fuel cell projects.

In the next five years, the most critical factor in maintaining, and potentially enhancing, the UK's competitiveness will be the launch of true commercial products, probably in niche markets. However, given the higher level of support provided to overseas competitors by their governments – approximately £180m-£230m in the US, £155m in Japan, and £67m in Germany compared to £12m per annum in the UK[122] – there is a risk that the UK's current intellectual property head-start will be eroded.

CENEX – centre of excellence
Imperial - UKERC- Supergen consortium
Toshiba
Bloom Box
SOFC – Siemens-Westinghouse, Planar Global, Ceres Power, St. Andrews, Imperial, Fuel Cells Scotland Ltd, QinetiQ, Rolls Royce
Alkaline- Alternative Fuel Systems Ltd, Eneco Ltd
PEM - CMR Fuel Cells, Dart Sensors Ltd, Intelligent Energy, Intelligent Power, ITM Power PLC, JM Fuel Cells, QinetiQ
Fuel Cells UK: UK Hydrogen and Fuel Cells Association
Govt- Dstl, NPL

2.6 Nuclear Fusion

Abstract

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.

Summary

Fusion made enormous progress when the current generation of devices, such as JET, were built, following the oil crises in the 1970s. This led to the production of 16 MW of fusion power, thousands of times higher than was possible before; however, a viable fusion power plant still remains elusive.

The first generation of fusion reactors will probably 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 with tritium. 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.[123]

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. ITER, 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, HiPER).

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, the Joint European Torus (JET), the world's biggest fusion device to date, located in the UK, and ITER, the new device being built in France. ITER, the International Thermonuclear Experimental Reactor, is designed to produce 500 MW of fusion power.

ITER is a global collaborative venture involving the EU, Japan, China, Russia, India, US and South Korea. The UK's own research device, MAST, is also the subject of much international collaboration.

The National Ignition Facility (NIF), at the Lawrence Livermore national laboratory LLNL in the US, is the world's most powerful laser. It is anticipated that NIF will demonstrate ignition and burn of a deuterium/tritium pellet by the end of 2012. This would be a key step to a programme of technology development, the construction of a prototype laser fusion reactor and the demonstration of commercial energy production. The timescale of such a demonstration depends on many factors, but making reasonable assumptions on the availability of funding and progress with the development of the technology, roll-out of commercially viable power plants by 2040 is possible.

There is also an opportunity to dispose of fission waste using a laser fusion plant in a hybrid scheme. Fusion neutrons would drive fission reactions in a sub-critical blanket surrounding the fusion chamber. Such a process, undertaken within a suitably controlled environment, could make a substantial contribution to the reduction of proliferation risk by reducing the amount of fissile waste.

Within Europe, through its leadership of the European HiPER Laser Energy project, the UK is well positioned to benefit from the opportunities of laser energy. During the three-year Preparatory Phase, HiPER has carried out an extensive programme of technology assessment, studies of commercial viability and identification of spin-out benefits. The findings are extremely encouraging at this stage and suggest a case for UK investment in a programme of technology development. Such a programme would be undertaken in collaboration with European partners and with the U.S. as recommended by the RCUK Review of Fusion.

Low-energy nuclear reactions – so-called **cold fusion** – remains a potential 'wild card': the US DOE 2005 assessment panel left the debate still open,[124] while apparently successful development work continues in the US Navy.[125]

Size of Market to 2025

It is possible that the first commercial laser fusion power plants could be online by 2040. The current economic model is for public funding of the technology development phase (c.£500m) followed by prototype power plant construction funded by private investment. The potential size of the market is large though unquantifiable until the economics of electricity supply are determined. Energy generated from fusion is expected to cost around €0.09 per kWh falling to €0.05 per kWh for early advanced plants. The price associated with carbon emissions would also determine the attractiveness of fusion power, with a high-carbon price further incentivising the use of fusion.[126]

Disruptive Potential

Given demonstration of ignition, burn and gain at NIF within the next two years and making reasonable assumptions of progress in the following Technology Development phase, it is entirely possible that laser energy could make a substantial contribution to meeting the 2050 energy supply and carbon emission targets. This would disrupt the energy market, reducing reliance on fossil fuels, and increasing security of supply.

UK capability

The UK is traditionally strong in fusion research, and hosts the world's largest device, JET. However, UK R&D spending on fusion since the 1980s has reduced compared to most other G8 nations. Progress in fusion research in the UK is strongly dependent on international collaboration.

In the laser arena, the VULCAN facility at Rutherford Appleton Laboratory supports a world-leading programme of high energy-density laser-matter interaction studies of direct relevance to fusion. Currently being upgraded to 10 PW capability, VULCAN will ensure that the UK maintains its leading position within Europe.

STFC's leadership of the HiPER laser energy project has placed the UK in an ideal position to drive the laser energy programme forward in Europe and to benefit from close collaboration with the US 'LIFE' project.

Institutions

The International Energy Agency[127]
ITER – www.iter.org European Fusion Development Agreement[128]
LLIL – NIF

HiPER
Culham Centre[129]
JET[130]
US Department of Energy[131]

2.7 Hydrogen

Abstract

Hydrogen is potentially the most important alternative to hydrocarbon fuels in future 'low-carbon' energy systems.

Summary

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 end-use 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.

Novel sustainable production routes are being studied including fermentation processes, photo-electrolysis and thermo-chemical cycles driven by solar or nuclear heat. Hydrogen can be stored more easily than electricity and has very high energy per unit mass.

Conventional storage and distribution solutions such as hydrogen liquefaction, which is energy intensive, requires at least 30% additional energy, and for mobile applications, space restrictions and hydrogen's low density mean compression to very high pressures of more than 700 bar is needed to maintain conventional vehicle range, with energy and safety implications. Research is focusing on solid-state storage using, for example, metal hydrides.

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 socio-economic and environmental costs and benefits: much data has 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. These can be summarised as:

- development of compact on-board hydrogen storage systems – ideally adsorbed in or on a lightweight solid medium for safety and energy reasons
- development of sustainable bulk hydrogen production pathways.[132]
-

Hydrogen may also have a role in the domestic energy sector. An advantage of hydrogen is that it could be distributed to homes using the existing natural gas grid, although there would need to be some modifications to pipework (as hydrogen leaks more readily than other gases). A programme in the Netherlands is currently exploring lining pipes to reduce leakage, and this could be significantly simpler and cheaper to implement than reinforcement of the electricity grid to deliver heating and mobility services. It should be possible to 'bleed in' hydrogen alongside, for example, biogas, to gradually decarbonise the gas grid. The inherent storage characteristics and peak-load energy delivery capacity of the gas grid (far higher than the electric grid) could act as a stabilising force in a hybrid gas-electric network.

2.8 *Microgeneration*

Abstract

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.

Summary

The Energy Act 2004 defines the scale of microgeneration as being up to 50kW electricity or up to 45kW thermal. However, the Green Energy (Definition and Promotion) Act 2009 sets a limit of up to 300kW thermal for heat in respect of the new Microgeneration Strategy, which should be published in 2011.

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.

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/nano-technology may permit power generation and storage via a wider range of techniques than is currently possible.[133]

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.

The potential market for microgeneration may be millions of homes and businesses. More than 40% of the UK's total primary energy demand is attributable to buildings. Large proportions of this energy are required for heating, cooling, ventilation and lighting of buildings and rely on fossil fuel energy generation. Energy conservation is vital in order to reduce the building-related energy demand. However, to achieve the Government's ambitious target of reducing carbon dioxide emissions by 60% of the 1990s value by 2050, building related microgeneration technologies need to play an important role.

Currently the vast majority of microgeneration installations are solar PV and solar water heaters. Greater and faster market penetration of other, less developed micro-technologies markets is likely to depend to a large extent on the availability of Government subsidies, which would also help stimulate demand for storage technologies. The introduction of Feed-In Tariffs (FITs) and the proposed Renewable Heat Incentives (RHIs), along with the Government's proposed zero-carbon homes policy, could act as a major stimulus for the microgeneration market.[134]

Trends

In microgeneration, while the UK has undoubted strengths in selected technologies – such as next-generation photovoltaics, heat pumps and biomass combustion – university and research capacity are weak compared with the UK's overseas competitors.

UK support for microgeneration generally lags behind that of other countries. For instance, Germany, a leader in this area, had 130,000 installed photovoltaic systems in 2007, compared to 270 in the UK. Furthermore, cost of installation in Germany was half that of the UK in 2008.[135]

Recent UK developments include the introduction of Government Feed in Tariffs for renewable energy, designed to help achieve the target of supplying 15% of total UK energy from renewables by 2020.[136] This is accompanied by the proposed Renewable Heat Incentive, which encourages use of technologies such as air- and ground-source heat pumps, biomass boilers, solar-thermal water heaters and CHP. There are indicators suggesting that FITs is having a positive impact on building mounted/integrated solar PV with increased interest and take up. There is also greater interest in solar PV farms up to 5MW.

Barriers and Enablers

Increased demand leading to a greater need for skilled installers and design capabilities.(There has been a shortage of inverters to meet demand in the UK market although current signs are more promising.)
Certification is playing an important role to drive quality and reliability in the marketplace and to boost consumer confidence.

UK capability

The UK has a small but growing manufacturing base for microgeneration technologies.

Institutions

See individual technology sections for main institutions.

- University of Southampton – sustainable energy research group, micro wind power, urban micro generation
- EcogenBaxi–mCHP application technology producing 1,800-2,400 kWh. Costs twice as much as a normal boiler price but reduces carbon footprint by 1 tonne a year
- Technology Strategy Board –Retrofit for the Future programme.
- ETI – energy storage and distribution – Macro DE project, costing £795,000, will study energy demand and supply profiles for sites, such as local services, hospitals and business parks, and equipment. The £1.1 million Micro DE project focuses on modelling the potential impact and operation of technologies in households
- DECC, DTI Hydrogen, Fuel Cells and Carbon Abatement Technologies Demonstration Programme
- Carbon Trust, EPSRC, Pilkington Group, Intelligent Energy Europe, EU

2.9 *Recycling*

Abstract

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.[137] There is a complex relationship, partly driven at EU-level, between recycling targets mandated by legislation and recycling that generates revenue.

Summary

There is significant market potential in recycling but barriers remain to market development. There is the potential significantly to improve efficiency and capacity by encouraging innovation and introducing more effective processes and improved technologies. This would save costs, energy, and natural resources, and would 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 (MBT), Mechanical Heat Treatment (MHT) and Material Recycling Facilities (MRF) facilities to produce recyclate streams for on-sale at market derived prices. This can avoid costs of multiple kerbside collections. However, cost issues remain – many of the recyclate streams have a market value far below their costs.

European legislation plays a strong role in driving development and markets. The EU has a range of regulatory measures, promoting a strategic approach to waste and resources, legislation regulating waste treatment; and management of specific waste streams such as end-of-life vehicles and waste electrical and electronic equipment (WEEE).[138]

Some of the waste treatment technologies that are emerging in the UK are linked to developments in biofuels. These include mechanical biological treatment, where waste is broken down, sorted and then finally digested with enzymes. This produces productive compost-like outputs and potentially some biogas, as well as increasing the recovery of recyclable elements from household waste. It can also produce Solid Refuse-derived Fuel (SRF) which can be used by industrial energy-intensive users as a fossil fuel substitute, although again, there are cost issues.

Research is also underway into the expansion of waste-to-fuel projects that aim to produce syngas, synthetic gas, from municipal waste.[139]

In this sector, recycling is driven by a requirement to meet mandated targets combined with the possibility of a revenue stream from recovered products – the hope is that the large volume of recycling forced by legislation will spur development of economically viable uses.

Past and current trends

The EU recycling sector has a turnover of €24 bn and employs about half a million people. It is made up of over 60,000 companies. The profile of these is 3% large, 28% medium and 69% small. Demand for raw materials is increasingly affected by global forces, and international trade in recycled material continues to grow. The EU has around 30% of world share of ecoindustries and 50% of the waste and recycling industries.

The UK recycling industry has a turnover of over £6bn, of which metals recycling, which is generally commercially viable, accounts for approximately two-thirds. Recycling of post-consumer waste has increased steadily over the last decade, from below 10% in 2000 to an average household recycling rate that is now over 35%.

2.10 Smart Grids

Abstract

Smart grids will complement the developments in power generation (see section on **microgeneration**) by intelligently accommodating the supply and demand requirements of all users to deliver high quality, sustainable and flexible energy, whilst preserving countries and individuals' energy security.

Summary

The current UK energy generation is characterised by centralised generation, using large coal, gas and nuclear power plants to generate electricity for use in a distributed network. With the advent of renewable power, and especially microgeneration technologies, there is an increasing need for a shift to decentralised power generation and the development of distributed networks that may form part of larger UK – or European-wide – network.

To match supply and demand, it will be necessary to develop highly accurate and coordinated systems to meet both peak demand and fluctuations in energy demand. Traditionally energy companies calculate how much energy generation is required up to a year in advance.[140] The intermittent nature of many microgeneration systems, including wind power and photovoltaics is not as reliable. Real-time, or near real-time control of supply and demand thus becomes more important to maintain security. **Energy storage** solutions or sources that can be rapidly ramped up on demand will become increasingly important. This is particularly so in the UK as it has less access to hydroelectric pumped storage than continental countries for geographic reasons.

One advantage of increasingly joined up grids will be the ability to utilise energy from different parts of the system to meet demand fluctuation. However, long-distance transmission results in energy losses, even with high-voltage DC transmission. Advances in **power electronics** will also be necessary to deal with the different levels of power transmission from microgeneration and in domestic and national grids, through conversion of electric power both between and within DC and AC systems.

To achieve two-way supply and demand matching, truly **smart meters** would be necessary to enable both consumer choice, and to allow data collection and transmission back to the grid, and to allow storage of power locally. This two-way communication would generate a large amount of data with the requisite analytics, network capabilities and control systems. However, the role of smart meters may be controversial. The rationale for smart meters is that users will adapt their consumption habits if they are charged different amounts for peak and off-peak usage – as demonstrated by the different usage patterns for households that have an ‘economy 7’ meter. Being able to monitor the cost of running different appliances in real time may also influence usage patterns, although there is as yet little evidence for this. A more ambitious rationale to justify the significant cost of smart meter installation could ensure that the operation of smart meters serves the consumer by encouraging genuine competition between energy providers, rather than strengthening a customer’s ties to an existing supplier. And if the smart meter is also a smart controller – capable, for example, of allowing the commercial operator to ‘reach through’ the meter to switch on and off household devices such as freezers that don‘t require continuous power – the ability of third parties (whether the electricity supplier or local grid operator) to regulate supplies may be challenged.

Significant infrastructure development will be necessary to upgrade distribution networks to accommodate two-dimensional power flows, and to install the necessary control systems.

Whilst a shift towards the ‘electrification of everything’ will increase the complexity of matching supply and demand by increasing the number of devices dependent on the grid for electricity, a move to electric vehicles presents an opportunity to utilise the electric batteries for storage and transportation of energy. Off-peak energy could be kept in reserve until needed.

Size of Market to 2025

DECC expect £8.6 billion will be spent on replacing 47 million gas and electricity meters, with an expected benefit of £14.6bn, over the next 20 years. UK transmission companies plan to invest £4.7bn by 2020 for refurbishment and expansion of their networks. The US market for smart-grid technologies is projected to reach nearly $17 billion by 2014, up from about $6.4 billion today, driven by an ageing electric infrastructure, increasing demand for electricity, and a growing reliance on foreign fuel sources, according to a study from Specialists in Business Information (SBI).

One major engineering company estimates that the global smart grids market will be worth €30 billion (£27 billion) over the next five years.[141] Building a European smart grid could cost a total of €150 billion (£133 billion).[142]

2.11 Solar Energy

Abstract

No single approach or technology stands out in terms of its potential to deliver, but it is clear that more research emphasis needs to be placed on manufacturing processes. Materials research aimed at improved PV devices must constantly take manufacturability into account. Although most of the research challenge lies in the design and manufacture of PV devices, systems are presently let down by underperforming system components and in particular the inverter – the part of the system that allows PV systems to feed electricity into the distribution system.[143]

Summary

Discussion of solar energy predominantly focuses on energy generation; however, solar energy can be harnessed for a range of applications including refrigeration and desalination. Three broad classes of solar technology exist that differ in their maturity, market penetration and applicability in the UK, namely photovoltaics, concentrating solar power, and solar thermal power.

Photovoltaics, or solar cells, are designed to convert solar energy directly into electricity. Photovoltaic (PV) technology has evolved steadily since it was adopted in the 1960s to power satellites in space. The first generation of devices were based on crystalline silicon and drew heavily on the knowledge of that material that developed out of the fast-growing electronics industry. Subsequently, a range of semi-conducting materials have been used to build photovoltaic cells but the most common remains crystalline silicon technology.[144]

Photovoltaic technology is carbon neutral at the point of use and estimates suggest PV could provide around 5% of global electricity by 2030 and 11% by 2050.[145] Estimates of the role of PV in the UK is subject to debate, and the UK is considered to be around 10 years behind countries such as Germany. The Government has introduced Feed in Tariffs (FITs) to subsidise PV in the UK, however the overall aim of research in PV is to reduce the costs of the electricity generated so that it can compete with conventional source generation, and other renewable sources. Some improvement in conversion efficiency is required, particularly for thin films, but this must be coupled to dramatically reduced production costs.

The efficiency of a solar cell is dependent on the spectrum of radiation that the semi-conductor can absorb, a property that is dependent on the band-gap of the material. The band-gap in traditional silicon cells limits their efficiency to around 15%.

PV research focuses on developing cells for terrestrial use, but also includes applications where optical concentrators combine with very small, high-performance, space-type multi-junction cells. Although the primary challenge is the design and fabrication of low-cost, stable, efficient cells that can eventually compete with bulk-generated conventional electricity, there are additional challenges associated with power conversion and minimising system costs.

PV systems could include dedicated arrays, such as those being built in Germany and Spain, at up to 3MW size, as well as devices designed to be integrated into commercial and domestic buildings – the latter are expected to be more common in the UK. The expected timeline for technology development, and the point at which PV technology will be able to compete without subsidy, is a matter of debate and will depend on the success of R&D and other factors.

In addition, some thin-film photovoltaic panel technologies are entering the market that achieve significant cost reduction by depositing semiconductor material directly onto glass or metal foil, minimising the amount of semiconductor material required.

A further area is **wide area organic photovoltaics** in which large expanses, potentially whole buildings, are used as the collecting surface. Such 'organic' solar systems may be cheaper and more sustainable but are likely to be less efficient.

Flat plate photovoltaic panels convert sunlight into electricity directly using semiconductor materials. When installed on a domestic roof, the electricity generated by photovoltaic panels can offset grid electricity. As photovoltaic panel manufacturing costs decrease, photovoltaic electricity is projected to reach consumer 'grid parity' (cost equivalent to paying for grid electricity) in locations such as Italy in 2010. UK consumer grid parity could occur by 2015 with industrial grid parity following in 2018.

Concentrating photovoltaic or **concentrating solar thermal plants** provide utility-scale generation in desert regions. Both employ mirrors or lenses to focus sunlight onto a receiver that either converts the sunlight into electricity directly (photovoltaic), or heats a fluid (thermal) that is used to generate steam to drive a conventional turbine.[146] Large-scale concentrator photovoltaic and solar thermal plants are suitable for regions with high levels of sunshine and are capable of generating gigawatts of electricity from a central installation. The energy can then be transported to population centres via high-voltage DC transmission. For the UK, this would involve joining European projects to build large installations in the deserts around the Mediterranean and North Africa, for instance the Desertec project which claims that 1% of the world desert would generate the same amount of electricity as is currently produced globally. Further research and development will be required, especially for concentrator photovoltaics where the first large scale (>100MW) field is under construction using >30% efficient solar cells.

In addition to large concentrating thermal plants, solar thermal energy can be used at a local level, for instance for **solar hot water systems**. This is a mature and cost-effective technology that accounts for more than 90% of installed solar energy capacity worldwide. The technology is sufficiently efficient and inexpensive to be economically viable in most locations and holds a self-sustaining position in the market.

In addition to active electricity generation, solar energy**, thermal mass** makes use of the properties of certain materials, e.g. concrete, that will absorb, store and later release significant amounts of energy. These materials can be used to reduce heat fluctuations in buildings, reducing and shifting peak loads. Solar energy can also be harnessed to split water to generate hydrogen, and to make chemical compounds.

Trends

Falling cost of solar energy, and increasing efficiency.

In 2006, the installed capacity for solar thermal was 127GW globally (0.176GW in the UK), mainly for hot water and space heating. China represents the largest market and also has by far the largest installed capacity.

The global 6.6GW (0.014GW in UK) cumulative installed photovoltaic capacity up to 2006, is mainly composed of cells made from silicon wafers, using processes inherited from the microelectronics industry. Growth in photovoltaic panel manufacturing (approximately 30% per annum over the past decade) means that the industry now uses more silicon than the microelectronics industry, making it feasible to produce dedicated ‘solar grade silicon’ on larger scales and using more cost-effective processes.

Large solar thermal plants are in operation in California, totalling 354MW, and several new 50MW demonstration plants are under construction in the Mediterranean. A 150MWe concentrator photovoltaic plant is under construction in South Australia.

UK capability

The UK has a strong solar materials science base, with strengths in innovative manufacturing research and translation. However, there are concerns over a lack of a central laboratory infrastructure. Compared to other countries, UK uptake of PV may be limited, due to a low relative abundance of sunlight, lower installed PV base and seasonal demand of electricity.

Institutions

- European Association for Renewable Energies EUROSOLAR
- European Solar Thermal Industry Federation
- European Photovoltaic Industry Association
- International Energy Association Solar PACES
- Fraunhofer Institute for Solar Energy Systems, Germany.
- National Renewable Energy Laboratory, USA
- UK research Initiatives: Uni Southampton, EPSRC + India, Unis Edinburgh, Cambridge, Oxford, Imperial College, Strathclyde, Northumbria, Loughborough
- Companies- Pilkington Group, DuPont Teijn, G-24i, The Solar Press, IPSoL Test, Solar Century Global Community Trust, New and Renewable Energy Centre, Leapfrog, IP Power, Perkin Elmer
- Narec Sharp and RomagCrystalox
- PV Net, British Photovoltaic Association (PV-UK), European Photovoltaic Industry Association (EPIA)
- Sharp, Romag, Crystalox and Solar Century
- G24i and Quanta Sol
- UK PV Manufacturers Association

2.12 *Intelligent Low-Carbon Road Vehicles*

Abstract

It will be necessary to both change consumer behaviour and to develop low-carbon transport solutions to meet UK 2020 carbon emissions targets. A range of technologies are 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 whilst maintaining individuals' access to personal and public transport.

Summary

The UK automotive industry is one of the most productive vehicle manufacturing industries in Europe with particular strengths in engine development and production.[147] Estimates of the value-add for automotive manufacturing in the UK suggest the sector contributes £10.2 bn, with a further £24 bn provided through the extended retail, service and maintenance sector. However, consumer use of cars accounted for 55% of domestic emissions, or 11% of total UK CO_2 emissions.[148]Furthermore, the domestic transport sector accounted for 21% of total UK CO_2 emissions.[149] The potential decarbonisation of road transport is significant. Innovation and improvement of existing technologies, such as developments in combustion technologies for 'conventional' internal combustion engines, forms a large element of current R&D.

However, to meet UK 2020 carbon emissions targets it will be necessary to both change consumer behaviour and to develop low-carbon transport solutions.

Traditionally, the **internal combustion engine** (ICE) and fossil fuels have been the mainstay of engine design. In recent years, new technologies and environmental concerns have led to the development of **hybrid engines**, which use an ICE to drive the wheels, as in a normal car, while also generating electricity to charge a large battery that feeds an electric motor (parallel hybrid, e.g. first-generation Toyota Prius). In some hybrid cars, the electric motor assists the engine when there is high power demand, such as for sudden acceleration or climbing hills. In other hybrids, the electric motor powers the car entirely at low speeds and when accelerating evenly. The engine kicks in only when the car picks up speed or accelerates suddenly. The environmental advantage of hybrid power is that under certain conditions, such as stop-start urban drive cycles, emissions are far lower than from conventional cars. The motor can act as a generator when the driver is braking. This allows kinetic energy, that would be lost as heat in normal braking, to recharge the battery, a process that makes a major contribution to a hybrid's fuel efficiency.[150] Vehicle manufacturers are currently focusing attention on series hybrids (plug-in hybrid electric vehicles or range extended electric vehicles). The motive power for these vehicles comes entirely from electric machines which are powered by battery (typical range 40 miles). Battery charging is provided by on-board ICE operating at maximum efficiency to extend the range of the vehicle to at least that of a conventional vehicle before refuelling is required. These vehicles have the advantage of also being capable of recharging from the grid.

Hybrid vehicles show reduced CO_2 emissions through greater fuel efficiency, but they are still dependent on fossil fuels. The alternative fuel market hopes to shift dependence on fossil fuels to low-carbon, or carbon-neutral, biofuels, including bioethanol, biogas and biodiesel. Alternative fuels have been used for decades in Brazil using cars that can run on varying percentage blends of ethanol and petrol. Their success in Brazil was based on an abundance of sugar cane and Government incentives; however, the relative cost of sugarcane and fuel has affected their popularity.[151]

In the UK, the majority of current investment has been around the development of fully-**electric vehicles** and **fuel-cell** powered vehicles.[152] Carbon emissions from electric vehicles are determined by the electricity source used to charge the car, and their utility determined by access to charging points. UK Government has started to pilot a charging infrastructure ('plugged in places') in various locations, with access points in car parks, major supermarkets, leisure and retail centres, and local streets. Electric cars also offer the potential to help manage UK electricity supply and demand, by taking advantage of off-peak generation (through smart charging at night) and by acting to store electricity as part of the grid. Issues with electric vehicles include their range and performance costs: estimates suggest that in 2020 the cost of a 15kWh electric battery providing a 100km range will be around $400, with the cost rising significantly for higher ranges. Furthermore the useful operational life of a battery for automotive applications is limited by the aggressive conditions under which it must operate.

The **fuel cell** vehicle market, although less mature than electric vehicles, could deliver low-carbon vehicles with greater efficiency and range than pure electric vehicles 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. TSB have supported the development of a fuel cell London Taxi.

Transport efficiency: There is also opportunity to influence the use of transport. Advances in information technology, GPS navigation and route planning, for instance, have already allowed UPS to increase fuel efficiency by minimising left-turns on delivery routes in the US,[153] which adds up to a large saving across the 880,000 strong fleet. Combinations of sensor technology with real-time GPS tracking and modelling have the potential to optimise UK-wide transport networks to maximise fuel efficiencies and minimise traffic jams. Consumer behaviour is also key; changing attitudes towards car-sharing, home-working and use of public transport could alter demand for personal transportation if the reliability and cost of public transport could be improved.

Intelligent Transport Systems (ITS): Intelligent Transport Systems (ITS) refers to intelligent vehicles operating on intelligent roads and relies heavily on Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. ITS enables people and freight to travel in the most efficient way, saving CO_2/energy and improving safety. A secondary effect is the efficiency gains to industry through improved freight logistics and operations.

Since the 1980s there has been recognition in the automotive sector of the potential of integrated electronic and communications systems to revolutionise the entire package of driver experience, road safety and traffic management. Recent developments and technological innovations (sat nav, on-board computer systems, increasing cheapness and effectiveness of in-car electronics, vastly increased range and accessibility of remote information) coupled with increasing pressures to address carbon emissions and traffic congestion are incentivising the UK automotive industry and Government (through the Technology Strategy Board) to make significant investments in ITS. The industry is keen to tap a growing global market for cars that deliver increased driver awareness and safety, particularly among older people. In the past two years, the UK auto sector has invested significantly in ITS projects in collaboration with the TSB – three distinct programmes have leveraged £12.5m private sector investment involving 25 consortia. A fourth programme, Informed Logistics, is at the final stage of TSB assessment, and a fifth competition, aimed at Incident Management, is planned to commence later in 2010/11.

Trends

The development of hybrid cars in the UK has been incentivised through a number of UK and EU initiatives, including the TSB Low Carbon Vehicles Innovation Platform.

The impact of electric vehicles is coupled to the emergence of clean and efficient electricity generation. The UK Joined-Cities Plan (ETI) and recent £30m Government trial for networks of electric vehicle hubs ('plugged in places') are promoting the adoption of electric vehicles within the UK, whilst Modec, a UK-based company was recently awarded a US contract for their electric trucks.

Hydrogen cars

- $600m in federal grants to the 'Big Three' carmakers in the USA to further development of battery technology for hybrids and electric cars
- US companies will receive $1.5bn to produce batteries and components and expand recycling capabilities
- $500 m will go to producing motors for electric cars
- $400 m will fund testing of plug-in hybrid electric vehicles (PHVs) and electric vehicles
- In the UK, the Technology Strategy Board is awarding more than £10m to develop ultra-efficient electrical systems for electrical and hybrid vehicles. It will also spend £25m to road test more than 340 low-carbon vehicles across the UK
- As part of the TSB's 340 vehicle Ultra Low Carbon Vehicle Demonstrator programme, the UK Government has awarded funding to Toyota and EDF Energy to support a trial of up to 20 innovative PHVs. The trial will start in London in 2010 for a period of up to three years. The intention is to lease vehicles to a mix of public bodies and private companies, including the Greater London Authority and the Government Car and Despatch Agency[154]
- The Joined-Cities Plan, announced in September 2009 by the Energy Technologies Institute (ETI), aims to help cities across the UK to deploy a network of compatible recharging points. The £11m plan has been created to support the roll-out of a single national network that will ultimately enable plug-in vehicles to be easily used and recharged anywhere, including the home
- Korea announces development of electric public transport, Online Electric Vehicle, utilising submerged electric power strips that provide wireless electromagnetic power
- The Government announced the roll-out of a £30m fund for a network of electric vehicle hubs – called 'plugged in places'. The project, lead by the Office for Low Emission Vehicles (OLEV), will see charging infrastructure appearing in: car parks, major supermarkets, leisure and retail centres,and local streets The first 'plugged in

places' were named today as London, Milton Keynes and the North East; and between them they will be installing over 11,000 vehicle recharging points by 2013

Institutions and vehicles

- BMW – mini E; Modec – US contract re electric trucks
- Vauxhall Ampera
- Gordon Murray Design and Zytek Automotive
- Tata Motors European Technical Centre (TMETC)
- Nissan Leaf
- Toyota Hybrid Auris
- Warwick Manufacturing Group
- Nissan European Technical Centre

2.13 Marine and Tidal Power

Abstract

Marine energy involves generating electricity from waves, tides, thermal gradient and salinity gradient (osmotic power). A wide range of marine energy technologies are 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.

Summary

The UK is a world leader in wave and tidal stream technologies and the global focal point for their development due to the level of resource around our shores, whilst the UK also has numerous tidal range sites, including the world's second-largest tidal range in the Severn Estuary. There are wider benefits and opportunities to embrace in the development of all these technologies, and to capitalise on the potential of the marine sector.

Estimates suggest that the practical resource level for wave energy in the UK waters is in the order of 50TWh/year. The total UK tidal stream is 17TWh/year. Taken together, wave and tidal stream could meet up to 20% of the UK's electricity demand. The UK also has significant tidal range resource with a benchmark energy output of 17TWh/year from a Cardiff-Weston barrage across the Severn. The other main tidal range sites could add to a further 1.8TWh/year.

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 potential 52TWh of tidal range energy generation possible in the UK each year[155].

Ocean Thermal Energy Conversion (OTEC) operates using a different principle to wave and tidal power being dependent on the natural temperature differential between warm tropical surface water and cold deep-sea water from depths of around 1000m.

A temperature difference of 20^{o}C 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 scaled-up.

Size of Market to 2025

Several UK based device developers are forming partnerships with the large utilities and system integrators, for example MCT and Siemens, and Pelamis Wave Power and EON.

UK wave energy resource – 52 TWh/year – 11 million households 2.5% global wave energy
UK tidal stream energy resource – 17 TWh/year – could power around 4 million households (9% of total global resource)
A global market in 2015 of £300m may rise to £25bn in 2020

Trends

The pace of development of marine energy technologies continues with many new projects being announced and more devices being deployed at EMEC (European Marine Energy Centre) and at other locations around the UK. Major utilities and the international energy companies are beginning to invest more broadly and deeply in marine energy.

Close links already exist between individual universities and device developers. The EPSRC-funded SUPERGEN Marine Consortium has 30 industrial collaborators, ranging from system operators to environmental groups and device developers.

Barriers and Enablers

Barriers:
Level of subsidy
Funding for R&D particularly early demonstration
Capital cost of the technology is expensive
Environmental regulation

Enablers:
Renewable Obligation: Emerging Technologies such as: Wave and Tidal technologies receive two Renewable Obligation Certificates (ROCs) for each MWh of eligible generation produced. However in Scotland the ROC level is set at 3 ROCs for Tidal and 5 Rocs for Wave.
Government funding for R&D
Commitment to meeting carbon emission targets.

UK capability

The UK has world leading testing and demonstration facilities at the European Marine Energy Centre (EMEC) in Orkney, Wave Hub in Cornwall and the National Renewable Energy Centre (NaREC) in the north-east of England. The UK is a world leader in the development of wave and tidal stream technology, utilising its strong academic base and leading expertise from oil and gas offshore operations and engineering.

Institutions and Technology Developers

- Aquamarine Power
- Atlantis Resources Corporation
- Carbon Trust
- European Marine Energy Centre (EMEC)
- NaREC
- Ocean Power Technologies
- Openhydro
- Pelamis Wave Power
- Rolls-Royce/Tidal Generation Ltd
- Technology Strategy Board
- University of Edinburgh
- University of Southampton
- Voith Hydro
- Wave Hub UK

2.14 Wind Energy

Abstract

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.

Summary

The past two decades have seen the generation of electricity from wind energy transformed into a major industry. Large-scale commercialisation of wind energy in the UK started in 1992 with onshore wind farms, typically using 300kW wind turbines. The technology has matured and developed rapidly and installed peak capacity in the UK has recently reached 5 GW,[156] including the latest multi-MW turbines (noting that, unlike a fossil fuel power station, which can run at capacity nearly all the time, availability of wind is intermittent; a rough rule of thumb is to divide the installed peak capacity for wind by three to get a comparison with conventional capacity, though some sites, for example offshore, may better this).

Several offshore wind farms are operational delivering over 1GW with construction under way at new sites to increase capacity by a further 1.4GW. Wind energy is expanding rapidly in the UK, and DECC estimates suggest wind could meet 30% of UK Government's targets for renewables, now set at 20% of total electricity supplies by 2020.

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.

Onshore wind is the most established market in the UK with 264 wind farms operating in the UK with a peak capacity of over 3.5GW.[157] Most onshore wind turbines, as with offshore wind turbines, are 'windmill-like' horizontal axis wind turbines (HAWTs). A variety of designs exist with the majority of 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 a GigaWatt (GW) of installed capacity. On top of this, projects with a generating potential of over 6 GW are in the pipeline, being either at various stages of construction or awaiting consenting or financing decisions.

The Crown Estate has awarded development rights for up to 32GW of new offshore wind generation under Round 3 of its leasing programme, in addition to existing plans and extensions of Round 1 and 2, all building on the country's geography and prevailing weather, and its expertise in off-shore engineering. The Government's Strategic Environmental Assessment found that 33GW of wind would not cause unacceptable adverse impacts on the environment.

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 GW. Estimates suggest 9GW of energy could be generated through small wind turbines by 2040.

A wide range of disciplines, from science and engineering to the environmental, geological and social sciences, participate in wind energy research providing information on the impact of building, operating and decommissioning wind turbines.

Trends

The amount of publicly funded wind energy R&D carried out in the UK has reduced substantially since the 1980s as the technology has matured and become increasingly competitive. By 2002, the direct publicly funded budget for wind energy R&D was £2.2m. The volume of R&D in the UK is now rising, prompted by the drive for efficiency improvements and cost reduction. Key players include further industry and several universities and research institutions.

Of particular note is the joint initiative from the Energy Technologies Institute and the Carbon Trust in 2008 to launch a £40 m programme to cut the cost of offshore wind power and to accelerate its deployment around the UK. In the recent Carbon Trust publication, *A Focus for Success*, offshore wind power was identified as critical for meeting UK climate change targets by 2020.[158]

UK capability

Decades of experience in offshore structures and operations in the gas and oil industry have put the UK in a good position to exploit its offshore wind resource, and to engage in overseas developments.

Despite efforts by Government over several decades, the UK is not a major player in wind turbine manufacture. However, the UK's capabilities in wind energy cover the whole range of technologies, from the design and manufacture of wind turbine generators, blades and towers, to resource prediction, monitoring, control, grid integration technologies, and onshore/offshore wind farm development and construction. Many international organisations are active in wind energy research, and are investing and collaborating with UK programmes including through the EU's Framework Programmes, and the IEA.[159]

The UK, along with Germany, are currently the key markets for offshore wind power, and the UK accounts for up to half of global offshore wind installed capacity, following the opening of the Vattenfall farm off Thanet, Kent.[160] The UK has well-developed skills in offshore and services, and the potential to develop a strong value chain, with the greatest competitive advantage in the secondary service sector.

The Biotechnology and Pharmaceutical sector

3.1 Agricultural Technologies

Abstract

The global population is set to increase from 6.9 bn in 2010 to 8.3 bn in 2030 according to UN mid-range predictions, with the UK population set to grow by 9.8% to 68 m. The rising population poses significant challenges to global agricultural productivity, compounded by increased competition for land, water and energy use. To date, technology has enabled food production to increase per capita despite a decline in availability of land:[161] however, new agricultural technologies are likely to be required to meet future demands. Agricultural technologies range from novel farming techniques to third generation crops.

Summary

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 wellbeing. 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 PCR-based tests will radically cut the time it takes to find and identify pathogenic bacteria in food, while increasing the sensitivity at which pathogens can be detected.[162]

Several genetically modified biotechnologies are ‘in the pipeline’ and ready to support development of crop varieties over the next decade; however, significant ethical and regulatory barriers still exist in the UK and many other countries over the adoption of genetically modified crop varieties.

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

Input traits. Existing commercial GM crops include herbicide tolerance and insect resistance, utilising non-plant genes, i.e. 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 (e.g. dicamba), resistance to a wider range of pests and diseases (e.g.

fungal-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 improved photosynthetic capacity. Drought-tolerant maize, in particular, is an emerging area with seeds expected to be commercialised in the United States by 2012 or sooner, and by 2017 for Africa.[163] This approach includes modification of plants to change quality characteristics for a higher value product, such as oils with higher content of omega 3, higher levels of vitamins, the production of plastics, improved animal feeds (altered protein, lysine and phytase contents), enhanced starch content and use for 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.

While the focus of research into these traits has concentrated on crops not typically grown in the UK, notably maize, soybeans and cotton, some commercial applications are being explored in crops that are relevant to the UK, such as oilseed rape, forage maize, potatoes and sugar beet. Also, some 'pipeline' traits could apply to crops such as wheat and sugar beet. These pipeline developments could improve the profitability and competitiveness of the UK's agricultural sector through lower costs and higher productivity if the technology is embraced.

To meet UK CO_2 emissions targets it will be necessary to decarbonise agriculture. Approaches could include use of engineered feedstocks to reduce CO_2 emissions from livestock; conversion of CO_2 to methane fuel; use of biowaste to synthesise biogas and syngas though anaerobic digestion; 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 fertilizers.

Artificial meat may alter the dependency on traditional agricultural meat supply and non-meat protein. A team in the Netherlands has succeeded in growing artificial pork from animal stem cells, although no commercial products have made it to the market.

New farming approaches could also alter our dependence on traditional farming methods. These include precision farming, where farming techniques are applied at a microclimate level; for instance, plants are fed only the nutrients and water they need at the time they need it, and vertically integrated agriculture, where 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 micro-electronics, 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 be inert until 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 and monitoring of soil conditions to improve application of water, fertilisers and pesticides (Joseph 2006). However, as with any new technology, the potential risks (on human health and the environment) must be investigated, and weighed against the benefits.

Size of Market to 2025

UK farming contributed £7.2bn to the UK economy in 2009[164] and this is likely to continue to grow in line with population. Global meat production was estimated at $1tr in 2009, growing to $2tr in 2050.

Disruptive Potential

Developments such as third-generation DNA sequencing of plant genomes may offer a new opportunity to exploit the UK's research strengths in plant science. They could enhance the pace and efficiency of the UK's plant breeding programmes, which provide the basis for all crop improvement (both GM and conventional). The identification of disease resistance genes and the development of molecular markers for specific resistances could lead to major advances in conventional, non-GM, crop breeding.

Advances in synthetic biology, molecular techniques and genetics may allow plants to be tailored to produce synthetic compounds including pharmaceutical drugs and biofuels. New agricultural techniques would increase farming efficiency while reducing land use.

Trends

In 2008, 13m farmers in 25 countries planted 125m hectares of GM crops globally. Within this, the EU accounted for about 65,000ha. There were no commercial GM crops grown in the UK. Both farmers planting GM crops and crop biotechnology companies have focused their business and R&D activities on crop species and locations that provide the greatest returns, meaning that the UK is neglected.

The traditional pesticide/crop protection sector is considered 'mature', with limited opportunity for market expansion, low margins and high R&D and commercialisation costs, though pests and diseases themselves are evolving all the time and require appropriate responses. As such, the development of crop biotechnology products is attracting increases in R&D funding. This research is looking into second- and third-generation biotechnology crops that include both quality traits (e.g. healthier oil profiles) and agronomic traits such as drought tolerance and improved nitrogen usage. By way of example, BASF and Monsanto are together investing $1.5bn in research in crops that are more tolerant to adverse environmental conditions such as drought.

A BIS (then BERR) commissioned study (January 2008) indicated that the UK had missed out on up to £1bn in investment by not being open to GM technology, and the projected shortfall is up to £2.5bn per year for the next five years.[165]

Barriers and Enablers

Barriers:
Uptake of genetically modified crops and food is limited by regulation, legislation and public concern.

Enablers:
Increased pressure on existing agriculture due to growing populations, threats of disease pandemics, global warming and changes to land resources, e.g. phosphate shortages, soil erosion and water resource concerns. Food price rises, hunger and environmental sustainability may also drive development of new technologies.

Applications

Nitrogen-fixing cereals; engineered crop feeds; crops for hostile environments e.g. plants that can use salinated water; agriculture for growing raw materials and pharmaceutical crops; designer gardening; carbon-neutral clothes/materials; food to counter obesity.

UK capability

The UK is strong in basic agricultural and plant research and associated fields, including molecular medicine and genetics. UK research organisations have been successful in securing funding in what is a highly competitive process, obtaining over €2.3 bn in the sixth Framework Programme (FP6). Agriculture is not perceived as an attractive career and there are shortages in niche skills within the UK. The UK also has a significant resource, the Millennium Seed Bank Partnership, which has collected over 10% of the world's wild species.

Institutions

- Six multinational companies – Monsanto, Bayer Crop Science, Dow Agrosciences, DuPont/ Pioneer, BASF and Syngenta –dominate the agri-business sector. Only Syngenta now has a significant R&D base in the UK at its International Research Centre at Jealott's Hill.

- Advanced Technologies Cambridge (ATC), a leading UK company in crop improvement, product characterisation and toxicological evaluation.
- Rothamsted Research – largest UK agricultural research centre.
- The Technology Strategy Board plans to invest £90m over the next five years though the Sustainable Agriculture and Food Innovation Platform in the Agri-Food sector with the aim of improving crop productivity, sustainable livestock production and the reduction of food-chain waste and greenhouse gas emissions from the sector.[166]
- John Innes Centre.

3.2 Medical Imaging

Abstract

Medical imaging plays a vital role in the diagnosis and treatment of disease, as well as enabling scientific research. Radiology uses radioactive substances, 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.

Summary

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 techniques, 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,[167] which combine both visible light imaging with near-infra red imaging of fluorescent biomarkers, can detect particular pathologies associated with tumours without the need for biopsy. Similarly, Colour X-ray or TEDDI imaging 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, diagnosis of neurological diseases and disorders are still in their infancy. Advances in understanding how the brain functions, coupled with improved *in vivo* neuroimaging, both at the tissue and cellular level, could yield healthcare benefits through, for example, improved diagnosis and condition monitoring of physical and mental states.

Brain imaging techniques such as functional magnetic resonance imaging (fMRI) provide a window into the workings of the brain. Neurologists and psychologists have also identified fMRI signatures of brain pathology that help in the diagnosis and treatment of disorders.

fMRI is used in pre-surgical planning to localise brain function. The technique could have applications in, for example, pre-symptomatic diagnosis, drug development, individualisation of therapies and understanding brain disorders. Early studies also suggest that fMRI could be used as bio-feedback for conditions such as chronic pain.

Scientists may also develop a better understanding of how the cells of the nervous system communicate chemically. This could pave the way for more efficient treatments of mental conditions such as depression. Current approaches, such as Prozac, result in wholesale changes to the brain, when what is probably needed is more subtle modification of brain function.[168]

As well as affecting neurosciences and diagnostics, improvements in imaging, coupled with appropriate chemistry and molecular biology to visualise molecules within cells, will have a big impact on the operation of routine pathology labs. There could also be advances in fields such as software design and neuro-marketing – the study of the brain's responses to products, marketing and other messages.

Size of Market to 2025

The global medical technology market is estimated at £150-£170bn with a compound annual growth rate (CAGR) of 5.9%.[169] The global medical device market is estimated at $300bn with 4.6% CAGR to 2013.[170] Europe spends around 0.55% of GDP on medical technologies compared to 0.84% in the US.

Disruptive Potential

Incremental advances in medical imaging technology are set to continue with increased resolution and better imaging. Disruption to the market may occur with improved targeting of imaging markers, for instance through the use of microbubbles and ultrasound for delivery, or novel nanotechnology-based techniques.

A shift towards 24/7 operation would be aided by the development of open-source standards and advances in wireless communication, while point-of-care diagnostics and miniaturisation of imaging equipment would enable new distributed models of care, for instance through screening booths in pharmaceutical stores. These technologies would also facilitate widespread preventative screening and detection of nascent diseases earlier than with current technologies.

Trends

Current use of scanning techniques to diagnose schizophrenia, detect thought patterns, and treat Parkinson's disease during implant surgery, and in the development of drugs such as Ritalin and Ambien.

There is an increasing move towards combination products that are physically, chemically or otherwise combined and produced as a single entity.

Neurofeedback is a developing area: Omneuron, a private company, in conjunction with Stanford University, is using real-time functional MRI (rtfMRI) to train patients in pain management techniques by monitoring the ongoing activity of their brains. Within a 13-minute session, patients can learn to control activity in different parts of their brain and alter their sensitivity to painful stimuli, allowing them to better control pain. Patients watched their brain's level of activity as seen by rtfMRI and were trained to decrease pain intensity through mental exercises, such as focusing on a part of the body where they did not have pain. In years to come, rtfMRI has the potential to add an entirely new treatment option for a whole host of brain-related illnesses including depression, addiction and dementia.

Barriers and Enablers

Barriers:
The integrated nature of the NHS and its procurement capabilities could act as both a barrier and enabler for the development of medical imaging technologies.

Enablers:
Increasing demand for healthcare provision.

Applications

Imaging technologies can be used for a broad range of diagnosis and treatment as well as for biomedical research, including cognitive neuroscience. Additional applications exist in other areas, such as the use of Terahertz imaging and colour X-rays in surveillance.

UK capability

The UK is a net exporter of medical technology with 20% of EU medical technology companies based in the UK. The market is dominated by the largest three players: GE Healthcare, Siemens and Philips.

Institutions

- GSK and Imperial College: £76 million research centre to make the UK a global centre for clinical imaging[171]
- No Lie MRI, Inc. and Cephos Corporation offer detection services using fMRI
- Neuromarketing companies Sales Brain[172] and Neurosense[173] (an Oxford start-up) use fMRI to gain insights into consumer behaviour[174]
- IBM and the Ecole Polytechnique Fédérale de Lausanne (EPFL) – Blue Brain[175] project to create a detailed computer model of the brain

3.3 Industrial Biotechnology

Abstract

Industrial biotechnology involves the use of biological resources to produce and process materials, chemicals and energy.[176] 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.[177]

Summary

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 process conditions/industrial scale-up
- biorefining and very large scale bioprocessing (VLSB)
- meso-scale manufacturing

Biocatalysts. 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 to 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.[178]

Engineered cell factories. Industrial biotechnology is poised to become even more commercially significant by facilitating the processes that convert simple, inexpensive renewable feedstocks into an increasing number of end products. The shift over the next 7 to 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.

Plant biofactories. 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. Biorefining is the coproduction of a range of fuels and chemicals from biomass. First-generation biorefineries operate throughout the world for the production of bioethanol, producing 17 m 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 a variety of useful coproducts that can currently 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 very large scale bioprocessing (VLSB).

Size of Market to 2025

The UK is expected to increase its global share of the industrial biotechnology market, with 8-11% growth per year corresponding to an increase to £4-£12bn in 2025. The global market for industrial biotechnology in 2025 has been estimated to lie between £150-£360bn.

Disruptive Potential

The pace of technology development will determine the rate of growth of the industry. Advances may occur in the reuse of commercial and industrial waste streams to generate energy, chemical and biological feedstocks. Recent advances in the use of algae to produce commercial fuel could reduce the reliance on traditional petrochemicals.

Barriers and Enablers

Barriers:
Facilities – demonstrators, e.g. for fermentation
Innovation/knowledge transfer
Skills

Public/commercial perception
Price and availability of petrochemical feedstocks
Genome sequencing cost

Enablers :
Standards
Procurement

Applications

Fibre-based materials for construction and auto industry; bioplastics and biopolymers; surfactants; biosolvents; biolubricants, e.g. for cosmetics, paints; chemicals; biodiesel; pharmaceutical products including vaccines; enzymes; fungi for food production, chemical feedstocks and waste treatment. Algae for fuel; waste treatment and energy production through anaerobic digestion; plant based carbon capture.

UK capability

While the UK is recognised in several technology areas of relevance to industrial biotechnology, the biotechnology and chemistry research base is not well engaged in the problem of converting the renewable feedstocks of the future. The Industrial Biotechnology Innovation & Growth Team (IB-IGT) of BIS recognised the need to build on the UK's expertise and stimulate industry/academic links. It recommended a single, virtual centre of excellence for more rapid exploitation of the technology as one way to achieve this.

Institutions

- Carbon Trust
- Technology Strategy Board
- BBSRC, EPSRC
- Centre for Process Innovation
- UK Biocatalysis Centre of Excellence, Manchester
- Photosynthetic leaf – Robert Kitney
- Wellcome-funded Biocatalysis Centre, University of Exeter
- Bioconversion-Chemistry-Engineering Interface, UCL
- Centre for Bioactive Chemistry – Durham
- Centre for Extremophile research, Durham
- Enzymology – York, St Andrews, Oxford, Manchester
- Engineering microbes to produce drugs, University of Cambridge
- John Innes Centre – agriculture, biotech and pharma
- Rothamsted

- IBERS, Aberystwyth
- Novel Agricultural Crops, York
- Biocomposites Centre, Bangor
- Marine and algal biotech – Scottish Association for Marine Sciences, ECMB, Institute of Aquaculture, Stirling, Aquapharm (novel methods for discovery, isolation and development of biochemicals from marine microbes – SeaRich)
- Green Biologics Ltd
- Cidexis – Liptor – RT production

3.4 *Lab-on-a-chip*

Abstract

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.

Summary

Applications of LOC devices include rapid in-situ 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, or 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.

Benefits of LOCs include miniaturisation of testing devices, efficient use of chemical reagents, improved bio-assay, and improved portability of detection and assay systems. Devices will have a wide range of testing and diagnostic applications including areas outside the medical sphere such as in-situ atmospheric monitoring.

Physicists and engineers are starting to construct highly integrated compact LOC devices. Using techniques such as 'combinatorial chemistry', researchers use these tools to automate the synthesis and testing of minute quantities of many thousands of new compounds, and biologists use them to study complex cellular processes.

In the healthcare field, LOCs promise new point-of-care diagnostic capabilities that could revolutionize medical practice through the introduction of eHealth initiatives in GP surgeries and on mobile devices. For instance, IBM has developed a capillary-based chip that will allow 1 drop of blood to be screened for different disease markers in 15 minutes.[179]

LOC devices also have a role to play in developing artificial biological systems with applications for diagnosis and testing. Researchers in the US have developed a microfluidic-based chip that incorporates lung and blood tissue to mimic lung function.[180] This 'lung-on-a-chip' is capable of carrying out oxygen and carbon-dioxide exchange and other basic lung functions, and was capable of functioning in living rats. The technique has promise in replacing animal models for testing as well as developing functional constructs for replacement of human lung tissue.

LOC devices will find uses in all areas where portable sensing equipment is required. Commercial exploitation has been slow, but is gaining pace, with some products now on the market.[181][182]

Size of Market to 2025

2.6bn USD in 2009 – 5.9bn USD in 2014.[183]

Trends

Cost of microfluidic technologies is falling with improvements in manufacturing techniques, and viable passive technologies. Low-cost techniques for manufacture will accelerate uptake, for instance low-cost assembly of LOC technology using cotton to stitch devices together.[184]

Barriers and Enablers

Barriers:
Cost of LOC technology.

Enablers:
Increased demand for personalised care and remote treatment
Advances in nanotechnology and materials research.

Applications

LOC technology has a wide range of biological applications including medical diagnostics, replacement of animal testing, organ repair and replacement, environmental sensing of pollution, tracing of GM products, nanotechnology detection.

UK capability

Development of biocompatible CMOS electronics (EPSRC – KTA), University Bath[185]/King's College London.

Institutions

- IBM Zurich – LOC-based diagnostics for flu, cancer, infections and toxins
- Dolomite – a leading manufacturer of microfluidic equipment
- Zeneca/SmithKline Beecham Centre for Analytical Sciences at Imperial College – LOC Amplification technology for PCR, reduced costs and speed

3.5 Nucleic Acid Technologies

Abstract

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 which 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 miniaturisation of techniques through LOC technology and as the cost of techniques such as gene sequencing continue to fall.

Summary

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 localisation 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.[186]

New approaches to traditional **gene therapy** which has traditionally focused on the replacement of defective DNA or on the introduction of novel DNA using a viral vector, are also likely as understanding of the role of RNA in regulating gene expression develops further. A new focus on single-stranded DNA, micro RNA (miRNA) and double-stranded RNA (dsRNA) technologies as therapeutics may lead to clinically-approved interventions for gene therapy and treatment of medical disease.

RNA interference (RNAi) may lead to new treatments. RNAi is a mechanism that allows particular sequences of genetic material to be ‘knocked-down’ or silenced in a controlled way. Drugs triggering this process are in development to affect different types of tissues. More speculatively, RNAi may offer scope for disrupting pathogen biochemistry, much like conventional anti-microbial drugs.

Viruses, bacteria or yeasts may be able to act as carriers for new sequences of DNA. Medical applications of this technology are referred to as gene therapy. The new sequences control key aspects of cellular chemistry, such as protein production. Beneficial uses already include treatment of certain immuno-deficiency diseases.

The correlation of gene mutations and variations in conjunction with epigenetic markers, such as histone methylation states, and miRNA expression will also increase our understanding of the complexity of diseases and medical conditions offering predictive tests and cures for a variety of cancers. Another outcome may be increased understanding of individual sensitivities to drugs.

Size of Market to 2025

RNA therapeutics has been predicted to be one of the fastest growing therapeutic classes in the pharmaceutical market by 2020. There is predicted to be a global market of $3.5 bn by 2015 and a CAGR of 100.7% between 2011 and 2015.[187]

Given the blockbuster potential of RNA-based therapeutics, some of the most strategically and financially significant deals between biotechnology and pharmaceutical companies in the past two years were signed around RNAi, antisense and aptamers.

Disruptive Potential

With the advent of **3rd generation DNA sequencers** offering whole genome sequencing for less than $10,000, the number and species that will now be genotyped is going to expand rapidly, as will Genome Wide Association Studies (GWAS) looking for mutations that underpin human disease. Direct RNA testing using chemical rather than enzymatic systems is now emerging for mRNA as well as miRNA, offering improved performance and cheaper analysis.

Successful knowledge and development RNA-based treatments would have a disruptive affect on medical treatment, and facilitate the tailored diagnostics and interventions required in the fields of personalised and stratified medicine.

Trends

DNA vaccines for AIDS, malaria, hepatitis B and certain cancers are now in clinical trials and may be available within 10 years. Increased deployment of high-throughput technologies to analyse DNA, proteins and other cellular modifications is providing new opportunities for biological computation and data processing.

One antisense drug, formiversin, for the treatment of CMV retinitis, was licensed by the FDA in 1998; however no subsequent drugs have been approved to date.

Barriers and Enablers

Barriers:
Regulation; cost of trials

Enablers:
Increased demand for novel therapeutics.

UK capability

The Sanger Institute has significant capacity for high-throughput sequencing. The NHS has significant resources in its pathology and tissue sample libraries to be able to develop new and important biomarkers for cancers, public health diseases and antibiotic resistant bacteria.

Institutions

- US Food and Drug Administration– approval in 2005 of the AmpliChip CYP450 – the first diagnostic based on DNA microarray technology
- Illumina – development of technologies for genetic analysis
- NimbleGen – commercial microarray production
- Applied Biosystems – development of chemiluminescence-based system to measure gene expression
- Sanger Centre – Genome Research Institute
- Acuity Pharmaceuticals – testing of a treatment for age-related macular degeneration (AMD)
- Cenix Biosciences – provision of RNA interference research services
- IC-VEC, UK – developing therapies for Hepatitis B and C, liver diseases and cancer
- RNAi Co, Japan
- Oxford BioMedicaplc – gene therapy

3.6 Omics

Abstract

Ever 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.

Summary

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;[188,189] 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.

Proteomics. 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 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 HUPO playing an important role in coordinating projects worldwide.[190,191] Furthermore, proteomics technologies are large and expensive, which means they are not available to the whole research community. We need to find ways to allow widespread use of proteomics tools.[192] 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.[193] 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. Clinical research also hopes to 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 on 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 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.

Applications

Medical research is poised to benefit greatly from increasing use of 'omics'. It offers the potential to develop better diagnostic and prognostic tests, to identify possible new therapeutic targets, and to head towards individualised patient therapy.

In agriculture advances in 'omics' will allow greater knowledge of the underlying processes of disease, as well as advances in designer agricultural crops and food.

Institutions

- Imperial College Chemical Biology Centre and EPSRC Doctoral Training Centre
- Interdisciplinary Research Collaboration (IRC) in Glasgow
- Proteome Sciences plc
- Two-Dimensional Gel Electrophoresis (2D-GE Nonlinear Dynamics) – Newcastle-based proteomics analysis software
- European Bioinformatics Institute, Wellcome Trust Genome Campus, Cambridge

3.7 *Performance Enhancers*

Abstract

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’ drugson 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.[194]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.

Summary

‘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 effects of alcohol with none of its drawbacks.[195]

GPs wrote more than 535,000 prescriptions for anti-hyperactivity drugs in 2007, double the level in 2002. The use of Ritalin is reported to be widespread among students in some countries during examination periods.[196] Other recent examples of performance enhancers include the introduction of fluoxetine to treat social anxiety disorder and sildenafil for male erectile dysfunction, and the use of modafinil for alertness in the general population.

Additional research has suggested that deep-brain stimulation, a focus of treatments for Parkinson’s and other brain conditions, may result in increased memory performance.[197] Various technologies, including performance enhancers, brain stimulation and computer-mind interfaces, are being pursued by the US Government.[198] Examples of established technologies include the cochlear implant, which is an electronic device utilised to reproduce sound by directly stimulating the auditory nerve. Other techniques being developed include transcranial brain stimulation and prosthetic brain chips, for instance the hippocampal implant proposed by Theodore Berger in the US.[199].

In the UK, Prof. Kevin Warwick at the University of Reading has developed successful techniques for the implantation of a device directly into nerves to link the nervous system directly to a computer, for ultrasonic input to the human brain, and for electronic brain-to-brain communication. Further advances include the direct control of devices, or robots, by the brain, with researchers reporting the use of monkeys and moths to control robots.[200]

All these technologies have the potential to both restore brain and nerve function, for instance to restore limb function in paralysed patients, as well as to augment or alter brain function beyond natural capacities.

Further options for performance enhancement include robotic exoskeletons that would extend normal physiological performance, for instance aiding in heavylifting. A prototype developed at the Berkeley Robotics and Human Interface Institute has been commercialised by Lockheed Martin[201, 202] and is capable of carrying loads up to 200 lbs, although with limited battery life.[203]

Negative aspects of performance enhancement include concerns around unfair advantages of using the technologies, as well as side-effects and addiction of performance-enhancing drugs, and perceived pressure to utilise these technologies.

Trends

Continued large increases in computing power and in technological innovation, together with publicly proven successes, are likely to increase the likelihood of HPE becoming widespread. However, ethical issues, negative public perception, over-regulation or slower rates of technological innovation may slow or prevent the rise of HPE.

Applications

We may be able to control our mental acuity, emotions and sensations – and sleep and wake on demand – thanks to drugs that concentrate a night's sleep into a few hours or allow us to skip bed with no ill effects, even in the long term.

Institutions

- Cortex Pharmaceuticals – Use of Ampakine molecules to alter learning, memory and attention
- Cytos Biotechnology and Novartis – drugs for smoking cessation and treatment of Alzheimer's
- Roche – targeting central nervous system to improve memory
- Cambridge Neuroscience – work of Barbara Sahakian – memory enhancement using modafanil
- University of Florida, Neuroprosthetics research group – neuronal implant that learns from experience
- Oxford Centre for Neuroethics – ethics and legality of brain enhancement

3.8 Stem Cells

Abstract

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 to 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,[204] 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.

Summary

Traditional stem-cell research has focused on two classes of stem cell, **embryonic stem cells** and **adult (or somatic) stem cells.** Both have the potential to become other kinds of cells and can differentiate to give rise to a range of specialised cells and tissues. In addition embryonic stem cells are theoretically capable of infinite self-renewal; adult stem cells, in contrast, are a finite resource and consequently harder to culture. The relative potential of adult and embryonic stem cells has been of considerable debate due to differences in their pluripotency, ethical objections and the risk of immune rejection or tumour formation.[205]

Embryonic Stem Cells are pluripotent cells capable of differentiating to become any type of cell in the body. The therapeutic potential for embryonic stem cells is vast and research has been the source of great hope, ethical and legal controversy, and international competition; however it is not known if ES cells will ever be of significant value. No commercial human embryonic stem-cell therapies exist although the FDA gave approval for a human trial of a treatment for spinal injury to Geron in 2009[206] (although it is currently on hold). Human embryonic stem cells are currently derived from fertilised embryos generating ethical issues surrounding the sanctity of human life. **Foetal** (the stage between embryonic and birth) **stem cells** are also being researched: the UK has given approval for a foetal stem-cell clinical trial for stroke.

Adult or **Somatic Stem Cells** can also be pluripotent although they are typically only able to develop into a limited number of cell types. Adult stem cells have been found in a wide range of human tissues, including heart, brain, liver and bone and have been used to treat disease for several decades in bone marrow transplants.

In 2007, US[207] and Japanese[208] researchers described methods to reprogramme differentiated cells to an embryonic-like pluripotent state. The cells were termed **Induced Pluripotent Stem** (iPS) cells. They promise the diversity of applications of embryonic stem cells,[209] have a reduced risk of immune rejection as cells can be taken from a host, re-engineered and re-implanted, and circumvent the ethical issues associated with embryonic stem cells.[210]

Mass-commercialisation of stem cells will required new methods for culturing stem cells and increased automation.[211]

Disruptive Potential

Stem cells offer the possibility of novel therapeutic treatments that could be applied to every system in the human body. These might include replacing malfunctioning liver cells or even growing entire livers to replace diseased ones; giving new neurons to those with brain damage and new heart cells to those with heart disease; therapies for Parkinson’s and Alzheimer’s diseases, spinal cord injury, stroke, cancer, burns, cardiovascular disease, diabetes, osteoarthritis and rheumatoid arthritis; as well as furnishing an endless supply of red blood cells for transfusions.

Trends

On 11 August 2004, the Human Fertilisation and Embryology Authority announced that it had granted a licence, for research only, to researchers at the International Centre for Life in Newcastle to perform therapeutic cloning for the first time. The Gene Therapy Advisory Committee, Dept of Health, oversees licensing in the UK, covering basic research, human-animal hybrids, and clinical trials for human-derived stem cell products.

Move of US legislation to allow research to occur.

Barriers and Enablers

Barriers:
Regulation can delay the time-to-market for stem cell therapies.
Ethical concerns may limit development and adoption of stem cell therapies.
Cost of treatments
Concerns over safety of some treatments

Enablers:
The ageing population may generate an increasing demand and market for stem cell therapies.
Reducing cost of genome sequencing

Applications

Traditionally a key focus of global stem cell research has been **regenerative medicine** – the repair and replacement of tissues and organs as treatment for a wide range of disorders, including neurological disorders, orthopaedic conditions, cancer, haematological disorders, myocardial infarction and cardiovascular diseases, injuries, diabetes, liver disorder, and incontinence. However other potential applications include drug discovery and target identification, and the means to reduce animal testing and the development of artificial gametes.

UK capability

The UK has strengths in stem-cell technology – a pragmatic regulatory regime has encouraged the growth of innovative companies and inward investment from leading world players such as Geron and Cellartis – tissue engineering and bioactive materials. A UK public-private partnership, Stem Cells for Safer Medicines, also supports the development of stem-cell lines for pharmaceutical testing applications.

The UK Stem Cell Bank is Europe‘s first centralised stem-cell resource, providing scientists with shared access to research on a variety of different human stem cells. The Bank was set up with the full support of the UK Government and with funding from the Medical Research Council (MRC) and the Biotechnology and Biological Sciences Research Council (BBSRC). Its aim is to enable the huge amount of research that is needed to better understand stem cells.

The UK has developed a robust regulatory system for stem-cell research, which is recognised as world-leading in its application to embryonic stem cells. Ten years ago the UK was one of the first countries to regulate the derivation of embryonic stem cells in way which facilitated important research while recognising ethical concerns. With research now being taken forward into products, the UK has worked to ensure that the safety of cells, tissues and cell-based medicinal products is regulated appropriately at the European level.

Despite the overall appropriateness of the UK regulatory system, there are some perceived difficulties in navigating the regulatory process, given the number of regulators and regulatory frameworks that apply to stem cells at different stages from derivation to application in a patient. Questions have also been raised over the clarity of remit and role of the different regulatory bodies. There are similar questions around the manufacturing process, which the UK Stem Cell Tool Kit was recently developed to address. The Tool Kit is a Government online regulatory route map for researchers and the first of its kind in the world to help navigate the regulatory process.

Countries which have more permissive systems, or which remain essentially unregulated compared to the UK, may offer more attractive research and investment opportunities because of perceived lower levels of bureaucracy. However, some of these countries, such as China, also have much greater public spending on stem cell research in general, so it is difficult to quantify the regulatory impact. There are also downsides to minimal regulation: one or two high-profile problems have been associated with poorly regulated stem-cell research. In addition, ethical concerns may limit the scope for collaboration with research in countries where standards of regulation are not so well developed. It is difficult to judge whether such countries will change their regulatory processes, but it is in the UK’s interest to seek to preserve the long-term competitiveness of its regulatory environment. This means being ready to adapt to changes in science (such as iPS cell research), and to facilitate regulation of different end products and treatments, while maintaining safety and ethical assurance.

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 US embryonic stem cell research only took place in the private domain until new legislation was enacted in 2009.[212] 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.[213]For instance, Japan is widely recognised for its iPS cell work, and there is increasing competition globally, particularly from the emerging BRIC economies, such as China.

There may be an opportunity for the UK to take a proactive stance in developing new markets around both 'allogeneic' stem cells (where cells are taken from a genetically similar donor) and 'autologous' stem cells (where cells are taken from the host, re-engineered and reimplanted). 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 was seen to be less well suited at present to develop an industry around autologous stem cells, although if regulations were relaxed, the UK's strength in health services and the high standards of its healthcare would place it in a good position to compete internationally in this field too.

A possible development path would be for treatments initially to be administered on an individual basis, through the NHS or private companies. The UK would in this way develop knowledge, skills and expertise that would place it in a strong position to take advantage of a future industry built around 'universal donor' allogeneic therapies – cells that can be used for multiple applications without immune rejection. Advances in manufacturing techniques and bioprocessing would be critical to the development of a donor model around allogeneic stem cells as current technologies are not scalable, and limit the generation of the large number of high-quality stem cells required.

Institutions

- Centre for Stem Cell Research, University College, London – Application of stem cells to cure blindness and heart disease
- MRC Centre for Regenerative Medicine – reprogramming skin cells to iPS

- University of Warwick – one of the first groups in the UK to be permitted to create animal-human hybrid embryos from which to derive stem cells (www.hfea.gov.uk/en/1699.html)
- Cambridge Stem Cell Institute, Cambridge University – work to develop cell-based therapies
- ES International – providing stem-cell research products, owner of six of the federally approved human embryonic stem-cell lines in the US
- Stem Cell Sciences Inc. – work on developing a treatment for Batten disease
- Reneuron – Phase 1 clinical trial of stem cell therapy for disabled stroke patients.
- Azellon – due to run clinical trials in mid 2011 for meniscal repair technology
- Imperial College, Tissue Engineering and Regenerative Medicine Centre

3.9 Synthetic Biology

Abstract

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.

Summary

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 US has engineered bacteria to produce artemisinin, a compound used to treat malaria. Artemisinin is found naturally in the wormwood plant but is costly to synthesise chemically or to harvest. The same methods could theoretically be used to produce cancer drugs, such as Taxol, 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 bio-sensing, decontaminating polluted land and water, and processing information. Nor is the potential limited to purely biological systems; there may be scope for combining the products of synthetic biology with developments in nanotechnology and robotics to create novel bio-nano hybrid life-forms, perhaps with significant sensing, computational and response capabilities.

Although the construction of novel, useful and reliable microorganisms from a set of standardised parts is not likely in the near future, work to achieve this is well underway.

Others are working on the construction of standardised sequences of DNA, **‘biobricks’** that could be inserted 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 MIT which aims to produce a library of standard genetic components (called ‘biobricks’) that can reliably perform a specific function and be connected to form novel genetic circuits.[214] 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.[215]

Current headlines in synthetic biology focus on the J. Craig Venter institute in Maryland which is working on creation of ‘artificial life’ and recently succeeded in constructing an **artificial bacterium** with a **minimal genome** that was able to self-replicate.[216] Whilst essentially a proof of principle, the techniques and methodology can be used to create artificial organisms with functions that have commercial applications. Research also seeks to extend and rewrite the genetic code to produce proteins that do not occur naturally, but that have industrial and medical applications.

Although synthetic biology offers considerable opportunities, there are, however, also areas for concern, in particular the generation of novel pathogens or modification of existing ones to increase virulence or defeat medical countermeasures.

Size of Market to 2025

The global research market for synthetic biology was $600m in 2006. This is projected to grow by $3.5bn by 2016.[217]

Disruptive Potential

Advances in synthetic biology offer the potential to revolutionise design of biological systems. New forms of life can be generated to manufacture designer compounds, whilst biological engineering can be applied on the micro and nanoscale to deliver novel robotic and computational devices.

Applications

The interdisciplinary nature of synthetic biology could yield a range of applications with implications for agriculture, engineering and processing, energy production and the pharmaceuticals industry. Examples of potential applications include:

Development of a cheap anti-malarial drug. The plant-derived compound artemisinin has a high success rate in treating malaria, but has been impractical and costly to produce by standard chemical methods. By building a new metabolic pathway in yeast and *E. coli* with genes from three separate organisms, researchers have created a bacterial strain that can produce amorphadiene. This precursor can then be converted into arteminisin, a drug that could be available in the next few years.

The beginnings of cheap and green, high-yield hydrogen production. Hydrogen could become an important alternative to fossil fuels. A novel synthetic pathway consisting of 13 enzymes derived from five different organisms has been developed to produce hydrogen from starch and water. This pathway is being developed further with the aim of producing hydrogen from cellulose, a more abundant source of carbohydrate than starch, which could provide hydrogen for fuel cells cheaply and easily.

Answers to environmental contamination. Communities of micro-organisms are responsible for most natural biodegradation. Bioremediation technology uses micro-organisms to clean up environmental contamination. The metabolic and genetic control mechanisms of these organisms could provide clues that help us to develop novel micro-organisms that can decontaminate the most potent pollutants.

Programmable cells for therapy. Pathogenic bacteria and viruses can identify and manipulate cells to produce harmful effects. Programming a bacterium or virus that can identify malignant cells and can deliver a therapeutic agent could have major benefits for treating cancer and similar illnesses.[218]

Over the next 10 years, synthetic biology may provide radical advances in areas such as biomedicine, synthesis of biopharmaceuticals, sustainable chemical industry, environment and energy, production of smart materials/biomaterials and security (counter-bioterrorism).

UK capability

Research in synthetic biology has largely been pioneered by US groups so far, although a small number of UK universities including Cambridge and Imperial College are involved in this work. A 2009 report by the Royal Academy of

Engineering[219] stated 'The UK can currently boast a strong global position in synthetic biology.' Within UK industry, Unilever is active.

Institutions

- EPSRC Centre for synthetic Biology and Innovation at Imperial College
- Five international collaborative projects co-funded by the NSF & EPSRC following a Synthetic Biology 'sandpit'
- RCUK networks in Synthetic Biology
- University of Edinburgh, arsenic detector, cellulosic biomass degradation
- Imperial College, Lotka-Volterra oscillator, urinary tract infection detection, bio-fabricator, logic gates
- University of Cambridge – biobricks, pigment production

3.10 Tailored Medicine

Abstract

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.

Summary

Current models for treating disease are based around the empirical prescription of drugs. Whilst 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.

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 is 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 to 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 with 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.

Disruptive Potential

Advances in personalised medicine will be dependent on our understanding of how genetic and environmental factors affect the efficacy of drugs and other interventions. As the cost of genetic sequencing falls and other diagnostic tests improve, the accuracy and cost of stratified and personal medicine will fall, allowing widespread adoption of these techniques.

Barriers and Enablers

Barriers**:**
Public concerns over data protection and misuse by NHS, pharmaceutical and insurance companies.

Enablers:
Falling cost of genome sequencing and other diagnostic tests.

3.11 Tissue Engineering

Abstract

One of the major components of 'regenerative medicine' tissue engineering follows the principles of cell transplantation, materials science and engineering towards the development of biologic 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 *in situ* 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 commercialisation of new products.

Summary

***In-situ* 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 reimplanted would potentially reduce immunogenic issues with transplantation.

Biomaterials. Typical approaches to tissue engineering utilise three types of biomaterial as scaffolds: 1) naturally derived materials, e.g. collagenand alginate; 2) acellular tissue matrices – e.g. bladder submucosa and small intestinal submucosa; 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 biologic 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[220] and 3D organ printing techniques[221] use different techniques to automate construction of 3D structures. Micro-masonry 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.

Size of Market to 2025

The global market for replacement organ therapies in 2006 was estimated at $350bn of which tissue engineering of skin, cartilage and bone was estimated to be $144.6 million with predicted growth to $2.1bn in 2015.

Disruptive Potential

As the world population continues to grow there will be an increasing demand for treatments to repair and replace damaged tissue. Furthermore, the UK demographic is ageing, with the number living past 80 set to double to 54 million by 2031. Improved methods, cell understanding and materials will lead to advanced techniques for tissue regeneration, theoretically allowing new organs to be grown and customised. Further advances in automation of tissue growth, including 3D-printing and micromasonry, would allow widespread adoption of tissue engineering products.

Trends

The first FDA-approved tissue-engineered product, Apligraf, entered the US market in 1998.

In 2008, the first tissue-engineered organ, a windpipe grown from a patient's own stem cells on a tracheal scaffold from another patient was successfully transplanted into a UK citizen.

Barriers and Enablers

Barriers:

Cost of tissue engineering limits adoption. Relaxation of US laws over stem cell research in 2009, and significant US investment may threaten to drive UK expertise abroad.

Enablers:

Scarcity of organs available for transplant on NHS. Public concern over ethics of animal testing.

Applications

The traditional focus of tissue engineering has been on growth and repair of tissues. Early commercialised products with FDA approval include Apligraf (Novartis) for wound repair and Chondrocelect (TiGenix) for repair of cartilage. In addition to repair, construction of new organs will be an increasing focus of future research, with increased automation driving new models of healthcare. Tissue engineering can also be used as an R&D test bed, for large-throughput screening and as a replacement for animal testing. Synthetic polymers, biosensors and functional constructs are also promising areas for future research.

UK capability

The UK is a world leader in regenerative medicine including tissue engineering. It is building a connected regenerative medicine and tissue engineering community to enable businesses in this country to provide leading-edge solutions for the global market. To help with this the Government has launched, through its funding agencies, a 'RegenMed' programme, consisting of a total investment of £21.5m. The Technology Strategy Board administers this programme and to date, over 40 companies have been approved to receive more than £4.5m to support research and development into regenerative medicines.

Institutions

Imperial College, Tissue Engineering and Regenerative Medicine Centre

University of Sheffield, Kroto Research Institute and Centre for Nanoscience and Technology

Institute of Medical and Biological Engineering, University of Leeds

Cross-cutting applications

Significant parallels with Stem Cell Research. Potential for application of tissue engineering approaches within Agriculture and Genetic Modification, Synthetic Biology, Human Brain Interfaces, Bioenergy and Biocomputing.

3.12 *Modelling Human Behaviour*

Abstract

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.

Summary

Understanding complex relationships, such as the links between diet, lifestyle and physical health, or those between environment, education, life-experience and mental health, relies on identifying and quantifying the sources of variation. Broadly, these are either genetic or 'environmental'. The ability to understand the variability introduced by genetics through accurate genotyping will make it easier to identify environmental effects, which are easier to manipulate.

Developments in mathematics, modelling and simulation will in turn make the visualisation and comprehension of complex relationships more tractable.[222] 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 variable 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 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.

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.[223]

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, are sufficient for the intended use of the model.

Trends

Increased computing power and storage capacity means that there are potentially no limits to the size of datasets and the number of variables that can be analysed, and the variables can also be measured across time. Social scientists make increasing use of simulation, for example by exploiting techniques from computer simulation games, as they learn to rely on computers and an aleatory (random) approach to knowledge that takes into account the vastness of available data.

Institutions

- The Isaac Newton Institute for Mathematical Sciences, Cambridge[224]
- NERC and EPSRC Environmental Mathematics and Statistics Programme
- E-Science Data Mining Special Interest Group
- Environmental Systems Science Centre, University of Reading
- Centre for Mathematical Biology
- Mathematical Institute, University of Oxford

3.13 Brain-computer Interface

Abstract

Direct connections between a human'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.

(Information for the rest of this section has been supplied by the Defence Science and Technology Laboratory (Dstl))

Summary

A **Brain Computer Interface** (BCI), which may alternatively be referred to as a direct neural interface or a **Brain Machine Interface** (BMI), 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, as outlined below.

Non-invasive BCI devices use:

> *electroencephalography* (EEG) – measures the brain's electrical activity using multiple electrodes placed on the scalp. It offers good temporal resolution, but set-up of the multiple electrode headsets can be complex, and head movements are limited. Small gaming devices with electrodes focused in specific areas combine ease of use and portability, and low set-up costs.
>
> *Magnetoencephalography* (MEG) – maps brain activity by recording the magnetic fields produced by electrical currents occurring in the brain, but requires expensive equipment.
>
> *functional magnetic imaging* (fMRI) – involves measuring changes in blood flow related to neural activity in the brain.

Optical topography –measures changes in blood flow using IR light. The most promising of these technologies is functional Near-Infrared Spectroscopy (fNIRS), which holds a number of practical advantages over fMRI. The technology is portable, fitting in to a laptop-sized unit, and takes advantage of wireless technology to allow greater freedom of head movement while being scanned.

Partially-invasive BCI techniques, such as *electrocorticography* (EoCG), measure the electrical activity of the brain using electrodes which are implanted inside the skull, but outside the brain tissue. It offers the advantages of higher spatial resolution, better signal-to-noise ratio, wider frequency range and lower training requirements than EEG.

Invasive BCI devices, which are implanted directly into the brain tissue, produce the highest quality signals, but are also prone to causing scar tissue build-up.

BCIs can be used to help repair, assist or augment human cognitive or sensory-motor functions.

<u>Repair/rehabilitation</u>

Artificial limbs– A team from the EU and Tel Aviv University has developed the 'SmartHand' which is an artificial hand directly wired into the nerves of a human arm.[225]

Restoring mobility– The Milan Polytechnic Institute in Italy has developed a brain-wave controlled wheelchair using EEG response to named destinations in the home.[226]

<u>Assist</u>

Reducing stress– The US company NeuroSky has developed a Bluetooth gaming set which monitors EEG activity to assess emotional states.[227]

Focusing attention– Interactive Productline from Sweden has developed a game called 'Mindball' which uses EEG BMI to allow a user to move a ball across a table when relaxed.[228]

Reducing information overload – The Cognitive Cockpit uses an EEG BCI to help reduce the information overload experienced by jet pilots.[229]

Monitoring cognitive functioning – Researchers in the US and Taiwan have been using wireless EEG to detect tiredness in vehicle drivers.[230]

Hands-free or remote control of devices

US company Extreme Tech has demonstrated control of WowWee's 'Rovio' (a mobile webcam) using Emotiv's EEG headset and Skype[231].
The University of Illinois has demonstrated the free flight of a UAV using EEG.[232]
The University of California has used a neural interface to remotely control a moth.[233]
Honda has used a BMI to control the robot ASIMO.[234]
Intel is developing a brain-sensing chip, using fMRI, to control a computer.[235]
The Dartmouth College (US) 'Neurophone' uses Emotiv to operate an iPhone.[236]

Augment

Non-vocal communications – DARPA's 'Silent Talk' aims to develop battlefield communication using EEG signals of intended speech.[237]
Enhanced training – The EU's 'MindWalker' project is developing a BCI-controlled robotic exoskeleton[238] and another EU programme called the Presenccia Project, uses a BMI to operate a smart home in virtual reality.[239]

Trends

Over the next decade, the convergence of information technology, nanoscale engineering, biotechnology and neuroscience are likely to lead to highly sophisticated bio-interfaces.

Application	5 years (2015)	10 years (2020)	15 years (2025)
Computing	EEG systems will become more common for BCI	Implanted brain chips for controlling computers	Hybrid computers using technology and organic tissue
Medical	Neural prosthetics replace lost limbs	Thought-controlled robots for personal healthcare Thought-controlled wheelchairs	
Security	Lie, truth and false memory detection	Commercially available thought-controlled robots	
Non-specific	BMIs become smaller, cheaper and less physically intrusive to wear	Commercially available implanted BCI solutions	

Applications

Applications	Opportunities	Threats
Communications	Silent speech interfaces Hands-free communication	As with any wireless technology, there would be the threat of hacking.
Computing	Hands-free computing Increased brain-computer communication speeds Increased understanding of how the human brain achieves vision etc. will inform developments in computer vision	
Medical	Physical enhancement Cognitive enhancement Monitoring/reducing workload Concentration training Relaxation training Rehabilitation	'Self prescription' of moods or pain relief Longer term effects– brain damage? Change in personality
Training	Computer-assisted learning More realistic training	
Security	Lie detection Remote control of robots and vehicles Covert surveillance	'Brain hacking' Behaviour modification Cheap 'systems' for surveillance
Non-specific		Personal responsibility? Change to personal identity Personal autonomy and privacy

UK capability

UK academia is well represented in BCI research. There is a large, multi-institution, multi-disciplinary BCI community, based at Reading University.[240] Professor Kevin Warwick is currently leading an ongoing EPSRC sponsored project which involves training a cultured biological neural network to control a mobile robot.[241] The University of Oxford is developing an EEG-based communication device based on

20 years of research in the brain sciences and recent developments in adaptive computing.[242] Imperial College has research groups specialising in neural prosthetics, and rehabilitation devices and robotics.[243] University College London is pursuing research into novel brain-machine interfaces.[244] The BCI Group at the University of Essex has a range of projects looking at BCIs and cites their lab as 'one of the best equipped labs for non-invasive BCI research in Europe'.[245] Research at Southampton University's Institute of Sound and Vibration Research (ISVR), aims to demonstrate brain-to-brain communication.[246] Newcastle University[247]undertakes research in basic, applied and clinical neuroscience. It has an active collaboration programme with the Riken Brain Science Institute in Japan[248] and links to the Monash University Centre for Brain and Behaviour (MUCBB) in Australia. The University of Glasgow is currently involved in the EC-funded TOBI (Tools for Brain-Computer Interaction) project.[249]. The University of Strathclyde has ongoing research in rehabilitation engineering, and specifically neuroprosthetics.[250] The 'Brain-Computer Interface and Assistive Technology (BCIAT) research team' at the University of Ulster undertakes research into both theoretical and applied aspects of intelligent assistive systems development.[251] Other institutions of note are the Serious Games Institute at Coventry University[252] and the Institute of Neuroscience at the University of Nottingham.[253]

There is no indication that the UK has any companies actively involved in producing BMI-related technologies. A search of Derwent Innovations Index patent database over the period 1980-2010 produced 106 records. A brief analysis of the results showed that:

- The top global assignees in academia and government over the last 20 years (with numbers of patents in parentheses) are the US, China and Singapore – specifically: University of Tianjin, China (6); MIT (4); Agency for Science, Technology and Research, Singapore (4); University of California (3); University of Florida Res Found Inc (3); University of Qinghua, China (3); Caltech (2); University of Florida (2); and Duke University (2).
- The top assignees in industry over the last 20 years (with numbers of patents in parentheses) are the US and Japan – specifically: Cyberkinetics Inc (2); Matsushita Denki Sangyo KK (2); Neurosky Inc. (2); Braingate Co LLC (1); Intel Corp (1); OCZ Technology Group (1).

3.14 *eHealth*

Abstract

eHealth 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. eHealth may help to deliver better care for less money.

Summary

eHealth has applications in the expansion of a personalised system of medicine where 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.

Lab-on-a-chip technologies could also bring diagnostics down to a personal scale, where patients can test themselves and transmit data electronically for analysis and treatment.

The gains in quality of care, provided at lower cost, that eHealth may deliver are important in a context where health expenditure in Europe is expected to increase from 9% of GDP at present to around 16% by 2020 on account of ageing populations with more chronic disease patients and higher expectations for healthcare.[254]

The fragmented European market, with its different social security systems, a lack of interoperability between systems and legal uncertainties, means that technical and organisational solutions for one country often fail to take hold in others. Standardising information exchange formats and certifying interoperable systems would help to overcome the operational barriers. Other useful measures include clarification and guidance for the application of legal frameworks, and creating networks of public procurers.[255]

The UK's National programme for IT (NpfIT), launched in 2002 – one of the largest public sector health IT projects in the world – aims to provide authorised access to patient information whenever and wherever it is needed. NpfIT set out to implement an 'integrated IT infrastructure and systems for all NHS organisations in England'. An important goal was to enable patients to make informed health choices. It also

set out to increase the efficiency and effectiveness of clinicians and other NHS staff. NPfIT aims to achieve these goals by:

- creating a NHS Care Records Service (NHS CRS) to improve the sharing of records of consenting patients across the NHS and provide patients with access to their own health records
- making it easier and faster for GPs and other primary care staff to book hospital appointments for patients
- providing a system for electronic transmission of prescriptions
- ensuring that the NHS IT infrastructure can meet its current and future needs.[256]

Trends

- electronic transmission of prescriptions – now the Electronic Prescription Service (EPS)
- more than 1.3 million hospital appointments booked electronically at a rate of 10,000 a day and rising, accounting for over 20 percent of NHS referrals for treatment.
- E-health integral part of EU's i2010 ICT competitiveness strategy

Digital and Networks

4.1 Biometrics

Abstract

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, retinal, vein and voice. Biometric technologies are becoming the foundation of an extensive array of secure identification and personal verification solutions.

Summary

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 IDs, secure electronic banking, investing and other financial transactions, retail sales, law enforcement and health and social services are already benefiting from these technologies.[257]

Biometric solutions have been rolled out across UK airports; however, UK Government has recently halted plans to roll-out biometric passports with stored fingerprint data.[258][259] 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 in an effort to bolster security, and may utilise similar technology during the Games. 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 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.[260]

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 debates surrounding the UK national DNA database,[261] and early concerns over the acceptability of DNA fingerprinting technologies used as court evidence.[262]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 development of biometric technologies and standards around a person's genome.

Size of Market to 2025

Data on the biometrics market was published by the market research and information analysis company RNCOS in its publication *Global Biometric Market to 2012*.[263]

According to a recent *Daily Telegraph* report, the UK market alone is 'worth £311m a year'. Globally, an industry already thought to be worth £1.2bn is expected to grow to almost £5bn by 2012.[264]

UK capability

The UK's contribution is most likely to be in systems design and implementation, in high-end systems integration and in algorithm development.

The UK has pockets of excellence and world-leading research within its academic research base,[265] including Kent and Southampton Universities, the National Physical Laboratory and UCL. The UK is well placed in face recognition, with important work developing in 3D techniques, iris scanning techniques and writer recognition/automatic signature verification.

Institutions and Applications

- Aurora Computer Services for face recognition

4.2 *Cloud Computing*

Abstract

Cloud computing is a general term for anything that involves delivering hosted services (e.g. business applications such as office suites, etc.) over the internet. Cloud services have three distinct characteristics that differentiate them from traditional hosting:

- they are sold on demand, typically by the minute or the hour
- they are elastic – a user can have as much or as little of a service as they want at any given time
- the service is fully managed by the provider – the consumer needs nothing but a personal computer and internet access.

Summary

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).

Infrastructure-as-a-service (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 the enterprise, cloud computing allows a 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 electricity, fuel and water are consumed, it’s sometimes referred to as utility computing.

Platform-as-a-service (PaaS) in the cloud 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, an outgrowth of Salesforce.com, and GoogleApps 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.

In the software-as-a-service (SaaS) cloud model, the vendor supplies hardware and software and interacts 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.[266]

There is debate around the environmental merits of moving from a traditional model with local data centres to a distributed cloud environment. The predominant view is that the scalability of cloud computing, with on-demand power consumption, will minimise power consumption and the number of required servers, and hence reduce carbon emissions. However, organisations including Greenpeace[267] have suggested that any long-term energy savings gained from switching to cloud computing will be negated by overall demand and changes in consumer behaviour. Adoption and optimisation of green cloud technologies would reduce energy consumption, for instance through efficient virtualisation technologies, uptake of new green data centres, or through a shift to renewable energy.

Key issues surrounding the utility and adoption of cloud technologies include: perceived risks surrounding the security of data – an issue for public, private and consumers alike; ineffective standards and interoperability within cloud environments; a need for clarity on data ownership, with the potential for disputes between user and service provider; and lack of user control over level of service and performance, with consumers having to rely on infrastructure outside their direct control. As a consequence the distributed nature of cloud computing will require new business models and legal frameworks to be developed.

No full-scale middleware exists which commonly addresses all cloud capabilities: management features and resource optimisation (even for generic PC optimisation), self-monitoring (resources, failure, free load, virtualisation).

Size of Market to 2025

Global revenue from cloud services is expected to grow 16.6% to $68.3 bn this year and more than double to $148.8 bn by 2014.

Barriers and Enablers

Barriers:

Some companies have concerns about security issues associated with the cloud for security reasons. In addition, jurisdictions in which data might be stored also differ in terms of how data is treated i.e. whether or not it can be inspected by the Government.

UK capability

There are opportunities at the EU level to extend and complete current cloud capabilities, by developing infrastructures, provisioning and advancing cloud platforms, working on services provision (including metaservices),creating ISPs with extended cloud capabilities, and consultancy (no clear understanding of how and when best to migrate to a cloud system).

Europe has a strong background in underpinning research and development, e.g. GRIDS, Service-orientated architecture.

The US has a better developed cloud infrastructure. The UK is dependent on non-EU providers, with comparatively weak development of new tech and few resource infrastructures. Opportunities may lie in setting standards, defining the private cloud space, integration with mobile devices, application provisioning, and new business models.

4.3 *Complexity*

Abstract

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, e.g. an ant colony is 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 the risk assessments to the modelling of consumer behaviour.

Summary

The complexity principle is finding applications in social areas such as:

- urban growth, traffic modelling – complexity theory has been used to alter the activity of traffic lights and reduce congestion
- modelling consumer behaviour, housing markets – simulating the likely effects of certain interventions, such as changing levels of stamp duty
- the growth of small, high-tech industries – by demonstrating how they affect each other in one locality
- use of health services.

Other fruitful areas for complexity theory include management, by introducing new perspectives on how organisations actually work, and economics, where agent-based modelling – which takes into account the behaviour of individuals and institutions – provides an alternative to classical 'equilibrium economics'.

Organisational breakdowns are also being looked at in new ways. Complexity theorists argue that such failures sometimes occur because complex problems have been artificially broken down into 'manageable' components – an approach that ignores the reality of the interdependence of these components.

The influence of complexity science is increasing in the areas of security, intelligence and nuclear proliferation research and in 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 understandings of leadership practice and decision-making processes to create new approaches to conflict resolution and resource management.

The ability to model human behaviour for security purposes may be shared by the enemy. We are already seeing terrorist organisations operating as fluid and complex networks to exploit the weaknesses of forces reliant on ‘command-and-control’ approaches to defence or intelligence gathering.

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 semantic technologies, for instance pattern recognition based on complex systems (e.g. human cognition) would facilitate development of novel searching software, for instance fuzzy searches.

Artificial systems of the future may be complex enough to have unexpected emergent properties.

Trends

Two key challenges for this emerging area are:

- overcoming the constraints inherent in traditional mono-disciplinary structures (both institutional and funding agencies) to maximise the potential of this cross-cutting science
- building the right level and nature of engagement with policy makers to have a real impact on real world challenges.

Institutions

The UK is a leading player in Europe, on the back of initial research investments in the fundamentals of complexity science.
The UK is a leader in the application of complexity science to real world challenges, such as energy distribution systems, demographic change, risk and resilience and predicting catastrophic events.

- Bath Institute for Complex Systems[268]
- Warwick Centre for Complexity Science
- Bristol Centre for Complexity Sciences
- University of Oxford complex systems research group.
- Complexity-NET, a UK-led ‘ERA-NET’ (EU collaborative research network involving eleven partner countries)
- Florida Atlantic University’s Center for Complex Systems and Brain Sciences
- NASA Intelligent Systems Division
- Santa Fe Institute, US
- University of Michigan’s Center for the Study of Complex Systems
- US-UK International Technology Alliance programme[269]

4.4 *Intelligent Sensor Networks and Ubiquitous Computing*

Abstract

Sensors for a wide range of environments (light, motion, magnetism) are becoming increasingly small and increasingly connected – to each other and to either embedded or remote processing power – and so will provide unprecedented access to information about the physical world, thereby allowing greater awareness of the current environment and so potentially increasing our ability to influence and control it, as well as detect and monitor changes more efficiently.

Summary

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.[270]

The monitoring of our personal health is beginning to shift from diagnoses based on physiological symptoms to those based on biochemical information obtained by sensor systems that analyse blood or other body fluids, or that read out the changing patterns of gene activity in our cells. As sensors shrink in size and power requirements they could provide constant, life-long, health-status monitoring.

The provenance and composition of products such as electrical goods are increasingly being indicated not by external labels or on packaging, but by electronic tags that are integrated into the objects.

Networks of sensors with embedded computing power will form a pervasive system – an environment with billions of intelligent or pre-programmed networked devices, providing people with services and information when, where and how they need it. In the longer term these interaction devices will disappear and microsensors will facilitate a move into an 'attentive computing' environment in which user interaction with devices will be through natural language, gesture and body language and in which networked, intelligent, adaptive, context-aware devices will pool their data to predict user needs, and either deal with them 'invisibly' or be prepared for the possible user choices.[271][272]

Sensor networks will benefit from a number of advances in different technology areas. Firstly, improvements in sensors themselves will continue to occur, driven by research and demand for increasingly small, low-energy and high performance sensors. The exact technology is hard to predict, for instance advances in health sensing will benefit from research into microfluidics and lab-on-a-chip technologies, whilst a range of technologies arising from materials research, including micro-/nano-electronic mechanical devices and photonics, will continue to derive new methods for detection.

However, despite this uncertainty, it is likely that sensors will become increasingly sophisticated. For certain applications, such as environmental monitoring, advances in battery technologies and energy scavenging will allow sensors to operate as self-contained devices, and integration of sensors with communication technology will facilitate establishment of increasingly complex sensor networks.

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. Whilst 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 associated problems for storage and processing. Advances in intelligent software, 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.

As sensors, trackers and microprocessors become cheaper, more compact and more versatile, we may move towards a ‘smart environment’ in which information about our surroundings is constantly being broadcast and responded to. This might ultimately lead to greater efficiencies in the use of materials, energy and other resources, as well as improved health, safety and comfort. But such a move also raises questions about accountability, privacy and confidentiality, as well as posing new challenges for data management.

With such advances, it is not difficult to imagine a future that is entirely dependent on an invisible technical infrastructure, much like the physical infrastructure of cities today. A report for the UN predicts ubiquitous network connectivity forming an additional cyberspace layer atop the physical world. Wireless networks, along with tiny web servers, could provide distributed network and internet access to embedded sensors, controls and processors.[273]

Trends

- Needs for wireless sensors, availability of open source hardware[274] to speed the take-up of the networks.
- The global nanosensor market grew from $185m in 2005 to $2.7bn in 2008 and is expected to reach $17.2bn by 2012.
- Nanosensors will represent 10% of the total sensors market in 2010.[275]
- Founding in 2002 of Dust Networks by a team including Kris Pister, a professor at the University of California, Berkeley, and the originator of the Smart Dust concept, and development since then of a wireless mesh networking system for sensing and control applications.

Barriers and Enablers

Barriers to the use of technologies include:

- data and information provenance – a measure of the credibility and reliability – and trustworthiness
- dssues of ethics, sovereignty, intellectual property, liability, confidentiality (commercial and by the public), privacy, data protection, freedom of information and other rights and obligations when detecting, collecting and processing data[276,277,278]

- integration of different disciplines and components into safe, efficient, trusted systems.[279]

Enablers of the development and use of the technologies include:

- economic growth
- empowerment of the individual citizen
- research in data-rich areas, such as genetics, space and particle physics – need to handle vast bodies of data
- standardisation and frameworks for interoperability and transferability
- fundamental benefits of new ICT-based tools and models – cf. introduction of calculus
- increase in open source models, e.g. Linux in application software.
- commoditisation of bandwidth.

UK capability

Formal techniques for sensor network design, management and optimization, University of Bath (Leverhulme Trust).

Institutions

The UK is a world leader in pervasive computing.[280] It has world-class research institutions, including Imperial College, Glasgow, Nottingham, Lancaster, Southampton, Cambridge, Loughborough and Edinburgh

4.5 New Computing Technologies

Abstract

Silicon-based computing has been a major influence on the 20th century and is likely to remain as 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.

Summary

Current computing technologies are based on integrated electronic chips, predominantly silicon. Moore's Law, which predicts that the number of transistors that can fit on a given area of silicon for a given price will double every 18-24 months, is often cited to describe the steady advances in computing power, as advances in transistor technology typically correlate with increased power.[281]However, there are conjectured limits to the size of transistors based on the need for reliability and quantum effects.[282] Despite these limitations, research has continued to develop increasingly small transistors based on novel approaches or materials and nanoscale transistors have been developed, for instance based on graphene[283]– measuring 1 atom by 10 atoms – and could be harnessed to allow transistors to continue shrinking.

Whether or not Moore's Law continues to hold, new technologies are being developed to allow computer power to continue to grow despite any physical restrictions on silicon-based transistors. Some approaches aim to improve the efficiency of existing computers, whether through increased resource utilisation or efficiency improvements, or through changes to how transistors operate, moving from high transistor power consumption to ensure reliability to a model that has lower power but is designed to eliminate stochastic errors[284], whilst other approaches represent fundamentally new methods of computing.

Significant research is underway to develop functional **quantum computing**, whichoffers the opportunity dramatically to alter the way that certain problems are calculated. [285] 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 one of multiple states simultaneously. Quantum computers can therefore perform calculations significantly faster than any current classical computer.

Quantum computers have been designed; however, to date most efforts have been resigned to operating with only a few qubits, when hundreds would be needed for a commercial system. However 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.[286] 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.[287] However, there is some concern 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.[288]

There is much uncertainty about when (indeed, if) a full-scale quantum computer will be operational. Some estimates say not before 2035, i.e. in 25 years' time. 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 will 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 Quantum Information Processing, 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. Whilst it is unlikely that DNA computing will ever supersede current computers, it has already been applied to applications such as biosensing, including for the detection and treatment of cancer[289]. 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 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. While 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 the correct answer out and is not reusable. The DNA approach is probably not well suited to 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 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 where waves carry information through a beaker of chemicals. Chemical computers could offer low-cost computing and allow development of amorphous robots.[290]

An alternative approach to chemical computing is being undertaken by UK and European researchers funded by the EU emerging technologies programme.[291] Researchers are developing chemical-based cells that can function in a manner similar to that of neuron, one of the key aims of n**eural computing**, which aims to simulate or build artificial neural networks.

Size of Market to 2025

Worldwide spending on ICT was $3.4tr in 2007 and is expected to reach $4.3tr in 2011, with annual growth slowing from 10.3% to 3.6% in that period. The UK is the fifth largest ICT market behind the US, Japan, China and Germany, with national ICT spending of $187bn.[292]

UK capability[293]

Major UK QIP centres of expertise include:

Academic – Universities of Bristol, Cambridge, Hertfordshire, UCL, Imperial, Leeds, Nottingham, Oxford, QU Belfast, Sheffield, Sussex and York.
Industrial - HP Bristol, Hitachi Cambridge, NPL, QinetiQ and Toshiba Cambridge.

4.6 Next Generation Networks

Abstract

Connecting homes to the internet over high-capacity fibre optic, rather than copper wire, will 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.

Summary

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.

By 2012, the Fibre-to-the-Home (FTTH) Council expects that 13 million people across 35 European nations will have their broadband delivered by fibre.

The cost of installing optical fibre in new developments is little different from copper, as both require the same underground ducting. BT is piloting the use of fibre to the home in a development of 10,000 homes in Ebbsfleet, Kent, where it will offer a range of packages up to a maximum download speed of 100Mbps. Some 250,000 new houses are built in the UK each year, so houses built between now and 2015 will make up around 10% of the housing stock by that time. BT has stated its aspiration to install fibre to many of these sites as standard, but current regulation requires it also to install copper.

Most large businesses pay for dedicated broadband access, usually by optical fibre. Small businesses, which often rely on the same broadband access as home consumers, thus stand to benefit more from fibre. Business applications that would benefit from fibre, particularly from faster uploads, include videoconferencing, and moving data storage and security offsite to be managed by specialist service providers.

Major telecoms companies argue that they do not yet see a business case to invest in fibre outside of new-build sites. They argue that there is limited evidence of demand for fibre and that most customers do not use all the bandwidth already available to them.

Consumers are not prepared to pay significantly more for fibre 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.

Reasoning behind an expansion of fibre optics includes:

- lead-time of several years for deployment
- predictions of demand have focused too narrowly on extensions of existing services (like television), while the full benefits of fibre would become apparent only once it is deployed
- telecoms companies base their business cases on a return on investment within a few years, but once laid fibre would not need to be replaced for at least 25 years

New investment models could finance deployment over the longer term by separating the deployment of the access network from the services provided over it.

4.7 Photonics

Abstract

The term photonics, or optoelectronics, covers a field that is analogous to electronics, but where 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 (e.g. in communications systems, the internet, computer processing and data storage), but further improvements in performance, and falls in price, in many applications are expected.

Summary

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.[294]

Photonics technologies are already pervasive with the US optoelectronics industry development association (OIDA) stating that 35% of all consumer devices have photonic components, whether in DVD players, or LCD-based devices including TVs.[295] Some of the uses and opportunities of photonics, such as the laser and the fibre optic cable, are already well established and form critical parts of our 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 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 consumer-demand for electronics and a growing need for low-energy solutions for infrastructure, such as data servers as system capacities and network traffic increases.[296]

Flat-panel displays are predicted to be the largest drivers of this growth, followed by photonic components, including photovoltaic cells and high-brightness LED devices (HBLEDs). HBLED technologies are already utilised in a number of applications, from backlighting of displays through to car headlights. Solid-state lighting based around organic LEDs and organic light-emitting polymers (see section 1.7) are also likely to make significant inroads into the domestic and commercial lighting markets, with the first commercial products now available for purchase. The success of both solid-state lighting and HBLED technologies is likely to be dependent on reduction in their production costs.

Photonics technologies are also likely to see increased utilisation in electronic systems, or through new systems based solely on photonics. For instance, in the telecommunications and computing industries increasing data transmission and network traffic will require increased capacity and the introduction of scalable infrastructure. Sustainable, low-energy solutions for both power generation and cooling will become increasingly important. In the short-term, upgrades to optical communications systems and the introduction of new hardware with optical interfaces would help reduce energy consumption; however, development of eitherintegrated electronic-photonic devices, including switches and silicon photonics, or purely photonic systems based on photonic integrated circuits and facilitated through developments in silicon photonics would be needed to meet sustainable energy targets.[297]

Additional developments in the photonics industry are likely to include increased miniaturisation of technology, for instance utilising quantum dots to detect and produce light, the extension of photonics to utilise a wider range of the available spectrum, as well as improvements in high- and low-power lasers.

We should expect:

- Massively increased bandwidth in the home and workplace, and to a lesser extent on the move, e.g. Worldwide Interoperability for Microwave Access (WiMAX) presents opportunities for reconfigurable ‘clouds’ that, to all intents and purposes, have unlimited bandwidth and are accessible on the move. WiMAX products are capable of forming wireless connections between them so that they can carry internet packet data.
- Memory capacity/density will continue to increase and price per byte fall.
- Processor speeds will rise while power consumption falls.
- Technologies to enhance processing and storage capacities.
- Developments in quantum computing.

Size of Market to 2025

The global optoelectronics market for 2008 was $356 bn, with the green photonics share of that market 8.1% or $28.9 bn. The 2009-2020 CAGR for global optoelectronics is forecast to be 3.1% whilst green photonics is forecast to be 19.6%. These growth rates translate into $493 bn in revenue for optoelectronic components by 2020, of which $261 billion or 53% is the green photonics market share.

Trends

Photonics manufacturing is likely to consolidate around a small number of major companies and expensive facilities. The UK is not a major player in semiconductor manufacturing. However, it had several leading suppliers of photonic components until the dot-com crash, principally major telecommunications equipment companies either based here or with major subsidiaries here (GEC, Nortel, and Agilent). Much of this capability has now been closed, sold or moved offshore.

Meanwhile, the UK retains a strong R&D base in photonics, mainly in universities. There is a risk of this base becoming divorced from commercial exploitation. However, opportunities will arise as photonics moves to a standardised, ‘foundry model’ in which many users have access to state-of-the-art manufacturing. Such a move will encourage the growth of photonics companies built around IP without the need for high-capital cost manufacturing, and could provide a way for the UK to benefit economically from its strong talent base in this field. This is so-called ‘fabless’ model has enabled electronics companies in the UK, such as ARM and Cambridge Silicon Radio, which design electronic chips for mobile phones, to flourish.

Applications

Photonic sensors, including fibreoptic sensors, have been the subject of intensive research over the past two decades for use in civil and military environments to detect a wide variety of biological, chemical and nuclear agents. Small, lightweight photonic sensors have been developed with high resolution, immunity to electromagnetic interference, harsh environment operational capability and multiplexing capability. Photonic sensors can utilise different components of the optical signal, giving rise to a large number of different sensor designs.[298]

Photonics technologies also have medical applications. Optical coherence tomography (OCT) is a relatively new diagnostic technology that incorporates photonics and provides high-resolution, cross-sectional imaging of ocular tissues *in vivo*.

Other emerging applications of photonics technology include:

- design, fabrication and measurement of devices for efficient conversion of solar energy into electricity
- sources and sensors for automotive and consumer products
- quantum-limited sensors for detection of acceleration, magnetic fields and encryption applications, environmental sensing applications.[299]

Cross-cutting applications

Display technologies
Lasers
LEDs and solid-state lighting– green photonics
Micro LEDs
Photonic transceivers
Graphene for photonics

4.8 Service and Swarm Robotics

Abstract

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 outside research laboratories have learning ability, decision-making capability or other attributes of 'intelligence'. However, the past decade has seen increased utilisation of robotics in agile manufacturing, logistics, medicine, healthcare, commercial and consumer market segments. Developments are likely in **service robotics**, where robots assist people at work, home or leisure, and **swarm robotics** where a group of robots self-organises to approach specific tasks.

Summary

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. However, more recently, there has been increased attention on **service robotics**, and **swarm robotics.**

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 underwater surveying and surveillance, industrial inspection and agricultural robots (e.g. robot milking machines). Markets for care robots and entertainment robots are also likely to be important.

Service robots have the potential to transform the competitiveness of service industries and non-engineering manufacturing sectors just as industrial robots have transformed the competitiveness of engineering manufacturing.

Traditionally the defence industry has committed significant funding to research and development of unmanned capabilities to conduct 'dull, dangerous or difficult' tasks. These range from unmanned surveillance, especially in difficult-to-reach areas, to complex tasks requiring frontline robotic combat units and unmanned vehicles carrying out stand-alone components of military missions. With increasing automation, **service robotics** is likely to have additional applications in search and rescue, security and infrastructure protection.

In healthcare robotics has already been utilised during surgery, to assist with operation or for remote applications. Non-surgical applications are likely to expand with a key driver being the ageing population, with increased demand for assisted living and robotic interventions to improve quality of life. Robotics has already been applied for certain tasks such as robotic prostheses for limb replacement,[300] and for physical therapy to aid dyspraxia.[301]

Robots will remain central to space exploration and to operating sensors and other devices in hostile environments. There is an increased need for automation in energy acquisition, as well as for environmental monitoring, infrastructure monitoring and repair, manufacturing and logistics. In the transport sector continued advances have been made in robotic applications to assist drivers with likely future developments including opportunities for intelligent control of traffic.

If the domestic robot sector develops as some predict, it has the potential to be as least as large a market as those of other domestic appliances. Some countries are betting on this becoming a reality, most notably South Korea which has service robots as one of its top 10 growth industries and which is spending about $350M per annum on R&D in this area.

Significant barriers still exist to realise widespread adoption of service robotics, notably the ability for robots to learn and adapt to situations, to perceive, and to carry out more dextrous tasks. Novel mechanisms and high-performance actuators will be required whilst there is a need for considerable basic research into formal methods for control, planning and perception. 3D visualisation and techniques for mobility will be needed to aid navigation, with opportunities for semantic navigation technologies incorporated with advanced sensor technology. Autonomous manipulation and improved techniques for grasping and manipulating objects will also be needed to allow new generations of robots to operate novel tasks.

The issue of physical human-robot interaction and the development of socially interactive robots is also key to ensuring widespread public adoption of service robotics, especially in the domestic market.

Swarm robotics is another area where development is likely to 2020. In swarm robotics, artificial intelligence and self-organising behaviour is utilised to allow relatively simple, discrete (and often relatively cheap) robotic units to coordinate their actions to achieve complex tasks beyond the capability of an individual robot.[302] The applications of swarm robotics are diverse, but they are typically suited to applications where physically distributed objects need to be explored, monitored or interacted with, for instance in environmental monitoring, search and rescue missions or automated construction. The key advantage of swarm robotics is that each swarm is able to interact, adapt and reconfigure without the need for human intervention. Furthermore, the loss of individual robotic units from a swarm does not affect the overall capability of the swarm to carry out tasks.

Size of Market to 2025

Current worldwide market is $3bn – $5bn, although estimates are hard to make due to the early and fragmented nature of the market. As some areas are experiencing 10% growth per annum (and in some cases up to 30%, albeit from a relatively low base), it is clear that the service robot market will exceed that of the industrial robot market (currently just under $20bn a year).

The domestic robot market is by far the biggest in terms of unit sales (around 99% or over 7m units per annum) although less than 20% of the market by value.

UK capability

RURobots[303] has carried out a study for TSB to characterise the capabilities and needs of the UK robot industry and supporting research community.

Institutions and Applications

- use of unmanned vehicles and aircraft to carry out military missions
- workerless assembly lines; driverless trains
- automated decision-support systems
- Carnegie Mellon University – work on ‘claytronics’, the term they use to describe using reconfigurable nanoscale robots (claytronic atoms, or catoms’) to form much larger-scale machines or mechanisms
- Laboratory for Neuroengineering, Emory University and Georgia Tech – Invention of Hybrot[304]

4.9 Searching and Decision-Making

Abstract

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.

Summary

Searching and decision-making technologies are increasingly available for processing and analysing massive amounts of data. For instance, Wal-Mart handles more than one 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. It also uses this data to help identify persistent trends and hidden links between factors, for example, types of consumer purchase and the weather.[305] Tesco has utilised these data mining techniques to get an in-depth insight into its customers and their behaviours, 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 nudges towards new but relevant goods. Since its introduction, this has helped Tesco to become the largest supermarket in the UK with a market share more than 10% higher than its nearest competitor, demonstrating data's immense commercial value.

Mathematical tools for discovering patterns in large databases, along with stochastic modelling, are likely to contribute to better decision-making in several fields. Advances in mathematical techniques and modelling will enable mining of this data to provide a basis for effective decision-making. Advances in data mining coupled to reduction of physical costs and increased expertise, are likely in areas such as national security and crime detection. These advances could come from the development of techniques designed to maximise the different capabilities of people and machines. This will require collaboration between mathematicians, computer scientists and psychologists, similar to existing collaborations between mathematicians, computer scientists, biologists and chemists on projects such as genome mapping and pharmacological research.[306]

New technologies for cooperation and a better understanding of cooperative strategies may create a new capacity for rapid, *ad hoc* and distributed decision-making. Within ten years, a range of nascent technologies and practices may come together in ways that enhance our ability to cooperate in both established and ad hoc groups. Examples of these tools for collective action include:

- Self-organizing mesh networks, which support new ways of creating and managing stocks and flows of information (see section 4.8).
- Community computing grids, which model efficient use of resources and solve complex problems.
- Peer production networks, which provide a framework for rapid problem solving.
- Social mobile computing, which builds contextual understanding of problems and dilemmas and fosters trust and group identity in ad hoc situations.
- Social software, which builds trusted networks and networked knowledge bases to enhance community confidence and organisation.
- Social accounting methods, which take advantage of rating, ranking and referral mechanisms to inform policy.

These new tools could support the emergence of new markets and create economic value by helping to overcome social and psychological obstacles to cooperative action. By eliminating middlemen, and placing creative power in hands of consumers, these tools could facilitate new kinds of trade and commerce.[307]

Proactive and context-aware computer systems that anticipate users' needs and perform tasks in a timely and context-sensitive manner may also have an impact within 10 years. By 2015 computer users could be moving away from foreground computing, where our devices and networks wait passively for our typed instructions or mouse clicks, towards new ways of interacting with computers in which delegated systems perform tasks proactively on behalf of users, taking into account the requirements of time and place. A range of complex automated tasks could be performed proactively if a mobile computing unit could sense a person, application or device's context.

Examples include:

- search a smart calendar and itinerary for available times and destinations
- preconfigure account logins and identities
- set appointments with colleagues

- search and summarise background data for use in transit and at probable destinations, including proactively searching for and caching background data for meetings with people
- distribute documents and work meeting products.

Change may be gradual as many small component systems become available one by one. But over time contextual computational processes will enhance personal and group productivity.[308]

Search engine technology is also likely to evolve. There is some doubt as to whether technologies including the Semantic Web will gain significant momentum and revolutionise the way the internet works; however, the concept of tagging objects as well as pages is likely to lead to changes to how the internet is searched. Search engines are already experimenting with picture, video and voice search technologies; new 3D visualisation and display imaging technologies could allow multi-sensory search modalities, for instance haptic displays allowing customers to search for, visualise and feel clothes online.

However, those whose vision encompasses a web of data argue that the evolution of the web got stuck at the document stage. What was supposed to be simply a step on the route to the interconnection of all manner of data and even objects over a common internet protocol has turned out to be a sticking point. Proponents of the web of data argue that the web is currently a jumble of 'unstructured' data, mainly contained in documents, and that by adding structure and 'meaning' to the data and text on the web – in other words by indicating what the data in documents or on databases actually are (a city name, an exam result, a delivery address) – a raft of new and powerful applications will be enabled. The kind of information that would need to be added is for the most part simple and intuitive – for example, a film guide would indicate that 'Casablanca' in its listings referred to a film and not a town. Thus:

- The accuracy and reliability of search would be improved. Searching for *Casablanca* [film] would filter out irrelevant search results to do with Casablanca the Moroccan city or tourist destination. Of course, Google's algorithms mean that in most cases a simple text search would do a good job for a basic search such as this – a quick scan by the user being sufficient to identify a rogue result. But machines are still very poor at distinguishing between text results such as these – so it is hard to develop applications that can confidently use internet data as the basis for purposes such as sourcing goods or making recommendations.

- With the web of data, many applications could run without the need for human intervention. There would be no need for carefully coded and regularly updated comparison sites: users could initiate a comparison search from a browser that would pull in the most up-to-date data on the web. To add value, an application would need to do something cleverer: not find the cheapest dishwasher, but, for example, find the dishwasher that would cost less over a 10-year period factoring in energy costs and service charges. Business-to-business stock monitoring and ordering applications would no longer require proprietary enterprise software, using a closed database of suppliers, but could be extended to any company publishing its terms and conditions in standardised format. This might provide more opportunities for SMEs to engage with the supply chains of larger companies.

Institutions

- Autonomy, world-leading data mining software spun out of Cambridge University
- University of Manchester, School of Informatics
- UK e-Science Data Mining Special Interest Group

4.10 Secure Communication

Abstract

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.

Summary

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.

Quantum cryptography employs the phenomenon of 'entanglement' to create such a system. This can be used to make the quantum states of two particles – for example, photons of light sent down an optical fibre –dependent on one another. Thus a measurement made on one particle, as would happen if someone eavesdropped upon the message, would instantaneously affect the state of the other, no matter how far away it was, such that the interference would be detected.

Quantum cryptography has been demonstrated in principle with fibreoptical communications, but it is still an emerging technology. Recent developments have included increasing the bit rate of quantum key distribution more than hundred-fold, 'which will allow QKD to be applied to optical fibre networks connecting many users'.[309]

The uptake of quantum cryptography has so far been hindered by the requirement to have unamplified fibreoptic links between the two sides of any system. This limited clients to large businesses and governments. However, the market could be enlarged by moves to utilise the unused (dark) fibreoptic cables which exist across countries around the world, for quantum cryptographic networks. This idea has been pioneered in the Netherlands by Siemens SIS.[310]

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. Does software that ‘sniffs’ the web for unlicensed uses of watermarked files constitute an invasion of privacy? And how secure are watermarks themselves to forgery – in other words, how solid are they as legal evidence?[311]

4.11 Simulation and Modelling

Abstract

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, training and education.

Summary

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.

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[312] 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.’[313]

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.

Modelling and simulation also offers the potential for better decision-making, including public policy-making, by increasing our understanding of complex relationships – e.g. links between diet, lifestyle and physical health, or between environment, education, life-experience and mental health.

Developments in mathematics, modelling and simulation will in turn make the visualisation and comprehension of the complex relationships more tractable. Applications include the increasing use of modelling in place of animal testing, use

of social identity theory in conflict management, and simulations and gaming in contingency planning.

A major barrier to the effective use of models and simulations of systems is our ability to model human behaviour adequately. Our understanding of most aspects of individual and group behaviour is currently insufficient for it to be coded in software for use in models. Significant research in partnership with the social sciences is therefore required.

The service sector provides opportunities to exploit modelling and simulation, with applications in the construction, retail and business services. Techniques could support strategic decision-making, the planning of capital projects and modelling of business processes, including response planning for extreme or potentially catastrophic events.

Size of Market to 2025

Modelling and simulation are widely used in the UK's most R&D intensive companies, the top 15 of which have a combined R&D investment in excess of £11.5 bn.[314]

UK capability

Recent international reviews of the science base have confirmed the UK's strengths in modelling and in key elements of simulation, such as high-performance computing and numerical methods, and recognise that 'the UK has world-class activity in the organisation of industrial mathematics'.[315]

The UK's supply network for modelling and simulation is distributed across university research groups, specialist consultancies and software houses, centres of excellence in larger companies and public sector technology centres such as those in High Performance and GRID Computing. Stronger coherence in this network will enhance the UK's capacity, better serve its users and open up international markets.[316]

Modelling and simulation cut across formal boundaries and require a multidisciplinary approach. The UK's capacity in the science base will be further enhanced by better collaboration between the key disciplines of mathematics, computing, engineering and the natural and social sciences.

4.12 Supercomputing

Abstract

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 computing resources. The major computer and internet companies are already recognising and exploiting the opportunity this offers.

Summary

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, is also known as grid computing, autonomic computing, adaptable computing, cluster computing, utility computing and agile IT.

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 CPU cycles that would otherwise be wasted are put to good use.

The idea of having computing processing power on tap is analogous with the infrastructure-as-a-service form of cloud computing (see section 4.2), where the infrastructure costs are entirely outsourced to a 'virtual provider'.

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 it will be necessary to operate a more centralised grid infrastructure with, at its core, a network of massive resource nodes (petascale supercomputers).[317]

Past and current trends

- The University of Illinois, the US' s National Center for Supercomputing Applications and IBM announce in 2008 'Blue Waters', a contract to build the world's first sustained petascale computational system dedicated to open scientific research.[318]
- IBM's Roadrunner at Los Alamos National Laboratory in the US heads the TOP500 list of the fastest supercomputers in the world with the first petaflop system.
- Construction by Shaw Research (US) of Anton, a specialised, massively parallel machine, which should be capable of executing millisecond-scale simulations of the molecular dynamics of one or more proteins at an atomic level of detail.
- Google's use of a massively distributed load-balanced network of thousands of generic Linux computers to build one of the largest and fastest growing cluster-based services, offering anyone on the Web free storage of videos and unlimited mail storage.
- Emergence of 'render-farms' selling services over the internet to special effects houses and film studios.

Institutions

- Globus Alliance – development of the Globus Toolkit for grid computing by an international community of researchers, and responsibility for the reference implementations of *de facto* standards for grid computing
- National e-Science Centre – support of research into grid computing architecture
- HECToR (High-End Computing Terascale Resource) (UK)[319]
- The e-Science Programme of the UK's Research Councils
- Google – construction of one of the largest and fastest growing cluster-based services
- Intel – Terascale computing research
  University of Westminster, Centre for Parallel Computing

4.13 *Surveillance*

Abstract

A wide range of technological developments will greatly increase the scope for continuous, widespread, surveillance. Potential benefits will need to be weighed against risks from the resulting loss or privacy.

Summary

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’ (AI) 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 ‘microdrones’ (small unmanned aerial vehicles), it could be possible to keep all areas and spaces be under surveillance, a possibility that is likely to raise major privacy concerns.

Institutions and Applications

The UK has been particularly active in research into image processing, with centres of academic excellence including UCL, Surrey, Oxford, Heriot-Watt, Edinburgh and Manchester. Closer to market, Kingston University carries out more applied research and has a Knowledge Transfer Partnership programme running with Ipsotek, a London-based company.

The UK also has world leading capability in certain niche areas, such as Circular-Orbit Synthetic-Aperture Radar (e.g. COSAR).[320] In sensors there is some excellent research, e.g. the Intelligent Sensor Information System programme at Queen’s University Belfast, but overall the sensors and measurement industry in the UK is not growing as rapidly as the global market.

4.14 Analysis of Very Large Data Sets

Information in this section has been supplied by the Defence Science and Technology Laboratory (Dstl)

Abstract

Very large data sets range from large, structured information repositories through to very large, internet scale, systems typified by their heterogeneity and volatility. Finding and understanding patterns and trends contained within them will potentially greatly increase our understanding of many aspects of the world.

Summary

The nature of very large data sets is constantly changing and their interactions (both between systems and between people and systems) is becoming more complex. The UK science base is currently focusing on aspects of the topic with no one group looking at the whole phenomenon. Major UK research thrusts include:

- Modelling the structure and both functional and non-functional properties of Large Scale (LS) datasets.
- All aspects of managing the information assets of LS data sets.
- Development of ontologies to enable the use of data on such systems.
- Use of Complexity Science to understand the evolution of such systems.

Disruptive Potential

The ability to find, combine and analyse key data and trends in very large datasets would dramatically augment military situational awareness, both physical and cyber. However, the threat is that third parties both state and sub state will develop the capability to use such techniques against the UK. This is a nascent area and there is a real likelihood of very rapid progress as we come to understand the problem space. This is a high impact technology and is recognized as especially important in the current/ongoing era of Irregular Warfare.

UK capability

There is considerable expertise in this area spread across Government, academia and industry. Much of this work is collaborative in nature.

Within Government, there is a substantial body of expertise in the extraction of data from large scale, multiple source networks, and in its fusion/manipulation to gain meaning. There is also research into sociotechnical aspects of behaviour mediated across very large scale networks. The work is done by a mixture of in-house, academic and industrial collaborators.

There is considerable work taking place in UK academia including:

The UK Visual Analytics Consortium[321] (UK VAC) research into the analysis of data residing in very large scale datasets. It is led by William Wong of Middlesex University and includes Imperial College, Swansea University, Bangor University and University College London.
The Large Scale IT Systems LSCITS (Large Scale IT Systems) consortium[322] led by Dave Cliff of Bristol researching into non functional properties of VLS networks and their associated data.
The EPSRC AKT programme[323] led by Nigel Shadbolt of Southampton University looking at the key aspects of data management which are described as data acquisition, modelling, retrieval, reuse, publishing and maintenance. This programme formally closed in 2007-8 but continues to represent the main UK researchers in this topic.
The ESRC Global Uncertainties Programme includes a £3M research thread to examine various aspects of Cyber Identity gleaned from VLS data sets.
The emerging ASPECT programme, led by Seth Bullock of Southampton University is looking to apply complexity theory across very large scale datasets.

There is considerable work in UK industry. Companies include:

IBM has carried out extensive work on the analysis of large scale distributed systems as part of their Gaia Net work which uses a grammar based analysis approach.
Detica who tend towards a pattern matching / ontology based approach.
The General Dynamics-led Data and Information Fusion (DIF) Defence Technology Centre (DIF DTC) which has carried out a work focused on the fusion and management of data on LS networks.

Institutions

- UK universities and industry: see previous section
- CERN
- US National Visualization and Analytics Center, Pacific Northwest Laboratory, Washington

4.15 Bio-inspired Sensors

Abstract

Bio-inspired sensors offer novel ways of detecting a wide range of phenomena.

Information in the rest of this section has been supplied by the Defence Science and Technology Laboratory (Dstl)

Summary

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 which exploit the principles underlying biological sensors without necessarily copying exactly the natural structures. Thus, bio-inspired sensors should be carefully distinguished from biosensors.

Emergence of bio-inspired sensing as a separate discipline has been reflected in the growth in the number of journals and conferences wholly or largely focussed on bio-inspired sensing. Many organisations have research programmes pursuing bio-inspired sensors and dedicated research laboratories are beginning to be established.

Much current bio-inspired 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. An insect eye based ultra-wide field-of-view optical sensing system accurately to detect and image distant targets has been developed and image processing techniques, inspired by the 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. Polarimetric and multi-spectral imaging systems have been developed for the detection of difficult targets and are bio-inspired in the sense that they mimic the imaging systems of insects and mantis shrimp.

Other notable achievements include biomimetic strain sensors inspired by the campaniform sensilla of insects developed for space applications (structural health monitoring and active control systems) and ultra-sensitive chemical sensors based on synthetic gated ion channels.

Disruptive Potential

In the sensors area, bio-inspiration offers the potential for self or situational awareness with greater sensitivity than currently possible (for instance, sharks can sense electric field strengths of 5 nano V/m compared to only ~ 1 V/m detectable by commercial meters) or greater portability (for instance, one of the latest generation gravity meters – the Air Sea II gravity meter – weighs 86 kg which compares poorly with the natures solutions). The visual system of the mantis shrimp is believed to be the most sophisticated in the animal world – allowing polarisation and multi-spectral (7 wavebands from the near UV through to red) imaging. This allows the animal to detect difficult targets using sensors weighing only grams and operating at ambient temperatures.

In its wider application, bio-inspiration is a potential source of threats – for instance, artificial life forms may have unforeseen and adverse consequences – but it is difficult to envisage any direct threats from bio-inspired sensors. The 'threat' may be the West's failure to exploit bio-inspiration whilst assuming others may do likewise. In fact, bio-inspired research is not confined to Western countries. China has a large and active sensor research community and its market is expanding very rapidly served by a fast-growing community of manufacturers producing large numbers of physical and chemical sensors. The automotive sector is a leading user of sensors and is aiding China's micro-electromechanical system industry. Even less strategically focused countries, e.g. Iran have active bio-inspired programmes.

Trends

Recently six 'Grand Challenges' for future bio-inspired sensor civilian research were identified including fabrication; bio-inspired networks; multi-scale, multi-functional systems and medical sensors and are expected to promote non-military, multi-lateral international research. A recent study of patent applications for bio-inspired technologies suggested that the world is currently half-way through an innovation cycle expected to peak around 2015.

DARPA's 'Nano-Air Vehicle' concept envisages an ultra-lightweight platform for surveillance and target detection, identification and engagement. This will require visible/IR imagery, acoustic radar, chemical detection and electric, magnetic and gravitational field detection. Only nano-sized bio-inspired sensors will meet payload restrictions. These sensors will be used primarily for military purposes and to meet the 10-20 year timeframe requires basic research to begin now with an appropriate continuity of funding.

Applications

Bio-inspired technologies developed in the future are likely to influence nearly all of the products that industry develops and produces in the future. Miniaturisation to produce micro- and nano-scale devices, together with associated system integration will lead to increased uptake and impact. Medical applications, such as nano-bots for diagnosis/treatment, are likely to drive civil developments. The use of autonomous machines (employed, for instance, in difficult or hazardous environments) are likely also to be civil drivers for the technology.

UK capability

Academia

Many UK universities have expertise in different bio-inspired technologies. The Centre for Biomimetics at the University of Reading is working with EU funding to mimic sensors in insect cuticles for airflow and strain sensors. The Insect Vision Laboratory at Newcastle University is studying the locust vision system. The Centre for Bio-Inspired Technology at Imperial College is developing silicon retinas, cochlears and vestibular processors for use in neuroprosthetic devices; also 'optogenetic' technology is being used to develop a new form of retinal prosthesis using to bring back sight to the blind. The Centre for Self Organizing Molecular Systems, University of Leeds is developing a novel toxicity sensor based on modification of biomembrane fluidity and organisation. Bristol University's interests in robotics has fostered a diverse programme including bio-inspired actuator and other materials as well as bio-integrative and bio-hybrid sensors. The University of Glasgow has many interests in computer vision including realistic approaches to modelling anthropomorphic vision.

EPSRC funded research includes: 'Next Generation Bio-Inspired Sensors and Smart Materials' (University of Durham, 3yr programme, £1.05 m, ends 12/11) which aims to mimic biological sensing and signal transmission mechanisms to develop sensors which interface naturally with the complex biological systems within the body; 'A biologically-inspired hearing aid' (University of Essex, £134k, ends 8/11) and 'Bio-inspired technologies' (Imperial College, £201k, ends 12/10) is developing new technologies based on complex biological systems and biochemical processes.

Current and recent BBSRC funded programmes include: ‘Molecular mechanism of voltage-gated ion channel peptides’ (Edinburgh and Bath Universities) – collection of structural data on ion-channel gating mechanisms; ‘Artificial signal transduction’ (Sheffield University) – synthetic trans-membrane signaling systems for molecular recognition and ‘Biological sensing systems’ (Silsoe Research Institute) – molecular imprinted polymers as bio-sensing systems for biological processes ultimately for clinical applications.

Industry

The Technology Strategy Board is managing two programmes to drive bio-technology-enabled innovation in industry. One of them, an initiative in regenerative medicine to be run jointly by the TSB, MRC, BBSRC and EPSRC, may exploit bio-inspired sensors.

The Systems Engineering for Autonomous Systems (SEAS) Defence Technology Centre comprises a UK industrial consortium which aims to research innovative technologies relevant to autonomous systems, at both whole-system and sub-system level and facilitate pull-through of the technologies into military capabilities. Consortium members include BAe Systems, MBDA Missile Systems, Roke Manor Research Ltd., Rolls Royce, Selex Sensors and Airborne Systems, AOS Autonomous Decision-making Software and CAE.

Institutions and Applications

UK: See previous section.
US: All Services, DARPA, NASA, NSF
AUS; DSTO, University of Adelaide
CAN: University of Alberta – National Institute for Nanotechnology

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