fst journal

The Journal of the Foundation for Science and Technology
(formerly Technology Innovation and Society)

Volume 17, Number 8, February 2003

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© 2002 The Foundation for Science and Technology. ISSN 1475-1704

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MOORE'S LAW

After the human genome sequence

Miami Beach, February 2003

This year, 2003, has all the makings of a wall-to-wall scientific conference to celebrate the 50th anniversary of the Double Helix, the now-familiar structure of molecules of DNA. The first bite at this cherry, 1-5 February, took place in a hotel on the garish strip of built environment overlooking the narrow strip of pristine Atlantic seaboard that is the real magnet for winter visitors to Florida.

Biotechnologists have been making the journey for 25 years, thanks to the institution of a winter symposium by the University of Miami and the scientific journal *Nature Biotechnology*. What more natural than that the symposium should this year subsume celebrations of the molecular structure that has made biotechnology possible?

Professor James Watson — with Francis Crick the author of the article giving the structure of DNA published in *Nature* on 25 April 1953 — turned up in Florida to signal his approval of the plan. He gave a curiously defensive account of the events of half a century ago and of the recent controversies about the degree to which he and Crick, at Cambridge, may have been helped by informal access to data gathered by Rosalind Franklin, a researcher at King's College, London.

Watson's stated view this month is that the structure of DNA would have been soon found, probably in 1953 and "probably by Rosalind Franklin (although we didn't know that at the time)". The question whether "we behaved correctly" has no clear answer, but "depends on your viewpoint". But, in Watson's view, he and Crick "deserved to get the answer": they had defined their goal clearly and they recognised the importance of a tangible and true model of the genes that are the stuff of inheritance.

Controversy

In all likelihood, this controversy is probably sustained only by the circumstance that the double helix turned out to be a much more compelling model of what genes are like than the authors of the model can have expected when they began work on it. Watson and Crick could have built their model of DNA without extraneous data such as X-ray diffraction patterns. In the event, they did not need other people's data, yet they could not have known that at the outset. So the controversy will probably never go away.

Meanwhile, biotechnology has plenty to celebrate. Now that the sequence of the Human Genome, or the structure of all the human genes and their arrangement within chromosomes, has been published, surely the patterns of inheritance of various diseases should have become crystal clear?

Sadly, as serious biologists have recognised all along, identifying genes in the human genome is much easier than telling what their functions are. Much of the winter symposium was, for example, given over to the inheritance of diabetes, in which several genes are known to play a part. The objective of would-be therapists is to unravel the function of these genes in the belief that understanding will make the design of effective medicines feasible. It is slow and painstaking work.

That supports the opinion frequently expressed at Miami this month that understanding the human genome will be a much bigger undertaking than has been the sequencing so far completed with such acclaim. Part of that difficulty is that some of the simplest ways of understanding what genes do in the body are not useable in this work. On the principle that the mouse is a good model of the human being, people are tempted to infer the function of human genes by removing, or otherwise disabling, the corresponding gene from a line of inbred mice. But if the function of the gene happens to be essential to the mouse, breeding may not be possible without it. Then people have to resort to the complication of causing mutations in the genes of interest, which is time-consuming.

Stem cell research

Pierre Chambon (Strasbourg) and Martin Evans (Cardiff) described other ways of understanding how genes function, the latter by the use of embryonic stem cells to make apparent some of the earliest steps in the transformation of a fertilised egg from a single cell to a complete organism. For a largely US audience, Evans's account of his use of embryonic stem cells excited open envy; in the United States, federally funded researchers are restricted in their use of embryonic cells.

British policy was also praised in relation to the circumstances in which research with human embryos can be permitted (under license). The use of implantation as the criterion for deciding between embryos on which research is allowable and those which are destined for regular birth was applauded as an empirical solution to an otherwise intractable philosophical conundrum.

Rudolph Jaenisch from the Whitehead Institute at MIT, who was one of those to applaud British regulations in this field, also sobered his audience with an account of some of the problems facing the cloning of animals. (Dolly the sheep had not yet died at half the age of her life-expectancy when the winter symposium took place.) Jaenisch argued that all recent experiments to clone animals been enormously inefficient, with a high death rate among newly prepared embryos, and that animals born apparently successfully harboured abnormal physiological conditions. Jaenisch, who is the world's most serious student of this subject, said that the existing cloning techniques obviously failed to mirror "whatever happens in normal gametogenesis"—the production of ova and sperms. In other words, the outlook for cloning, for animals no less than people, has seriously dimmed.

The other highlight of the symposium was a plea by Professor Leroy Hood (University of Washington) that biologists should pay much more attention to the handling of the vast amounts of data now being accumulated about the behaviour of proteins and other vital chemicals in the working lives of cells. Most proteins, he argued, do not have a single function in the cells they inhabit, meaning that their interactions among each other are best represented by interlocking networks of chemical transformations. He looked forward to the emergence of a new discipline called "systems biology". But that revolution, he believed, would take a long time to come about.

Sir John Maddox FRS

Dear Sir…

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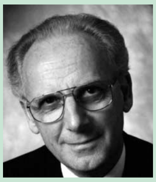
You cannot have your cake and eat it

Sir Brian Heap FRS

Science, technology and sustainability

This was the title of an FST discussion meeting held at the Royal Society on 22 May 2002. During the evening three speakers—Brian Heap, Professor David King and Sarah Roberts—debated how science and technology can support the drive towards creating a sustainable economy. The discussion was summarised by Jeff Gill.



Sir Brian Heap is Master of St Edmund's College, Cambridge and Special Professor in the University of Nottingham. He was formerly Director of the Institute of Animal Physiology and Genetics Research (Cambridge and Edinburgh) and Director of Science, Biotechnology and Biological Sciences Research Council.

In 1992, the UN Conference on Environment and Development at Rio de Janeiro recognised that current global patterns of consumption are not sustainable: there was over-consumption in the affluent North, under-consumption in less developed countries of the South. Much has since been done to mitigate the adverse effects of both over- and under-consumption, but the richest 20 per cent of the world still accounts for 86 per cent of private consumption, the poorest 20 per cent for only 1.3 per cent.

The concept of sustainable development may be generally accepted, but sustainable consumption rarely finds its way onto the agenda. Indeed, the very idea is often regarded as a threat to competitiveness, to profitability—and even to politicians' prospects of re-election. It is also seen as an imperialistic device to prevent less developed nations from achieving legitimate aspirations.

Sustainable consumption is not about consuming less, but about consuming efficiently—differently—while improving the quality of life. Sustainable consumption aims to achieve a balance between production, use and renewal of the resource base and therefore lies at the heart of the concept of sustainable development.

Global trends

Between 1950 and 1999, grain and energy output, GDP and population increased between twofold and fivefold. Consumption is expected to continue growing faster than population in the next 50 years, as the new consumers of nations such as China, India, Brazil and South-East Asia exercise their purchasing power. If such trends were to continue, 'business as usual' could not be sustained unless alternatives are discovered and adopted. There is scant evidence of an intergenerational concern that caters for the reasonable needs of our grandchildren.

Population growth has been influential. Consumption of meat and timber per capita has increased twofold, car ownership fourfold and the use of plastics fivefold. The poorest 20 per cent has increased its consumption hardly at all.

China is a striking example. If China increased its consumption of beef from 4 kg per person per year to match the current 45 kg in the United States, it would absorb the equivalent of the entire US grain harvest (343 million tonnes). Already meat intake in China has increased by 105 per cent during the 1990s; China has become the world's biggest meat consumers. If and when China matches the USA in cars and oil consumption, it will need 80 million barrels of oil a day (current global output is about 65 million barrels).

Population momentum also drives consumption because populations with a high proportion of young people continue to grow even after the birth rate has declined to two children per family.

Towards sustainable consumption

In 2001, UNEP put forward two principles for a transition towards sustainable consumption. One is 'dematerialisation', achieved by increased efficiency in resource production, novel production methods and better tracking of materials and energy in industry and general consumption. Among the tools that governments can use to encourage different patterns of consumption are the internalisation of the external costs of resource use. UNEP's second principle is to encourage consumers to use resources more wisely by providing them with better information and by raising the question of 'appropriate consumption', which turns on the deeper question of whether or not the quality of life in civic, cultural and religious terms is increased by consumption.

What are the opportunities and rewards that could make sustainable consumption a win-win strategy? Biotechnology has a demonstrated capacity to be part of the solution by producing more food on the same land. This is crucially important because the land on which crops grow is decreasing in extent, while the environmental impact of intensive farming demonstrates that we have been living off capital rather than interest: agriculture must change.

The global area of GM crops has increased substantially in the past six years. Many millions of hectares of commercially produced transgenic crops have been grown and the global market for GM products has increased from $75 mildiscussion

World Summit. Some surprise was expressed that the speakers did not say more about the forthcoming World Summit on Sustainable Development. This was expected to look at science and technology that could be transferred to the Third World—from North to South, as one speaker put it—to deal with such immediate concerns as food, water, security and health. Science and technology were seen as having much to offer here, one example being the work in India on the use of IT and satellite communications to help farmers. The right orientation and implementation were essential, with transfer of skills and knowledge and a focus on near-term problems. Pharmaceutical companies, for example, were not seen as addressing the diseases of poverty.

The final rejection of the Kyoto Protocol by the American government was seen as creating problems for the rest of world. The question was how to persuade the US to take CO_2 emissions seriously. One speaker thought that the US should not be demonised, since other developed countries had almost as bad a record.

lion in 1995 to more than $3billion in 2000.

The second wave of GM crops includes insect- and virus-resistant plants that reduce the chemical burden on the environment—'dematerialisation'. The crops will store better, with less wastage. Crops are being developed that carry iron, vitamins (vitamin A precursor in "Golden rice" for example), vaccines and enhanced levels of anticancer compounds. Among cash crops, genetically-engineered cotton has been adopted in South Africa because the yields are increased by 32 per cent while the use of chemical sprays is halved.

Physical materials present different problems. The average use of materials (excluding water) in the USA is more than 60 kg per person per day. If the global consumption of materials were to become as intensive, materials usage would increase sixfold and environmental damage would rise similarly.

Yet there are immense opportunities for dematerialisation in the material sciences. Over the past century in rich countries, the per capita usage of materials (industrial minerals, metals and timber) has grown in an S-shaped pattern: fewer materials are required for a unit of production. Steel consumption per person has either remained constant or has decreased. Aluminium cans now weigh 40 per cent less than a decade ago. An office building needing 100,000 tons of steel 30 years ago can now be built with one third as much.

Recycling is another strategy of dematerialisation. European motor manufacturers will be required to recycle 85 per cent of their vehicles' weight by 2005, rising to 95 per cent by 2015. These goals will make great demands on the ingenuity of engineers concerned with production, fabrication and distribution.

The revolutionary Beddington Zero Energy Development ("BedZed") in the London Borough of Sutton is meant to demonstrate that dematerialisation, combined with careful optimisation, can yield financially viable home construction. The project consists of 82 homes on a 1.4 ha former sewage works and a combined heat and power unit based on gasified wood technology producing enough electricity for the whole project. Solar energy from BP photovoltaic cells will power a car pool of 40 electric cars, low allergy construction materials will minimise respiratory complaints, built-in recycling facilities will reduce waste by 80 per cent and live/work arrangements will reduce the need to commute.

Families have just started to move in, the site will be fully occupied by July (2002) and it is claimed it will become carbon-neutral within another month. It is a serious attempt to achieve a level of sustainable consumption through science, technology, imaginative design with funding from, among others, the WWF UK.

Cornucopians, as Vaclav Smil calls them, claim that technology fixes will resolve impending crises. The opportunity presented by the world market for energy efficiency, recycling, waste management and pollution control has been estimated to be more than £500 billion per annum—strong competition for the global aerospace, car and chemical industries.

Catastrophists question, however, whether the fixes can deliver in time. The 850 million long-established consumers in rich nations are being joined by new consumers in 20 developing and transitional nations. (The latter already possess 22 per cent of the cars that contributed significantly to the increase in CO_2 emissions during the 1990s.) Time is not on the side of policy makers.

Informed consumers

Another approach to sustainable consumption highlighted by the British Government's Global Environmental Change Programme is the need for better indicators of economic progress based on secure scientific information. GNP as an economic indicator fails to account for the net value of changes in the value of the environment/resource base, so that consumers do not know the true costs.

Several attempts have been made to deal with these externalities. One of these is the Index of Sustainable Economic Welfare (ISEW), which estimates that, in the UK, GNP per capita was 2.3 time greater in real terms in 1990 than in 1950. In terms of the ISEW the increase was only 3 per cent and the average year on year growth rate was just 0.1 per cent. The chief contributors to the difference between these percentages were the depletion of non-renewable resources, long-term environmental damage and ozone depletion.

Fiscal instruments can also mould changes in consumption patterns, but require rigorous assessment of effectiveness. Subsidies may valuably make good deficiencies in the marketplace, support the disadvantaged and promote environmentally-friendly technologies. But 'perverse subsidies' as depicted by Myers and Kent[1] can have adverse effects on the economy and the environment.

The global ocean fisheries catch costs about $100 billion to bring to the dockside where it is sold for $80 billion, leaving a shortfall of $20 billion made up by government subsidies. The result is a depletion of major fish stocks, bankrupt businesses and sizeable unemployment. Greater sophistication is needed to avoid over-consumption.

Human behaviour

Even with better information about the real costs of over-consumption, Thomas Princen and colleagues[2] have argued that insatiability is axiomatic and that reduced consumption will come about only through scarcity or the imposition of external authority. Material consumption has become an integral part of meeting social needs and the pursuit of happiness.

The epidemic of obesity shows that even high-quality scientific and public information about the health risks is insufficient to alter consumption. It may be that evolution has better equipped us to defend against body weight loss in times of scarcity than against body weight gain in times of affluence. I note that the rich countries now spend $40 billion on slimming aids, a sum similar to that estimated for the Third World to eliminate malnutrition by improved agriculture.

Nevertheless, people do have a remarkable capacity for rapid change: take, for example, the unacceptability of smoking. Perhaps the future emphasis should be on the scientific understanding of the public rather than the public understanding of science.

To conclude, I believe there are opportunities and rewards for scientists, technologists, governments, industry and consumers in a commitment to sustainable consumption as a strategy for sustainable development. The dangers are that we fail to grasp the opportunities or underestimate the rewards. Norman Borlaug, father of the Green Revolution, recently warned that "hungry people are angry people". There is little doubt that Borlaug's foreboding attaches as powerfully to other gross inequities of consumption. ❐

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1. Myers, N. & Kent, J. *Perverse Subsidies* Island, Washington (2001).
2. Princen, T., Maniates, M. & Conda, K. *Confronting Consumption* MIT, Cambridge, Mass, (2002).

Climate change: a vital issue

Professor Sir David King KB ScD FRS

Sir David King is Chief Scientific Adviser to the Government at the Office of Science and Technology, DTI. Previously he was Head of the Department of Chemistry at the University of Cambridge and Master of Downing College.

I shall deal with the most important issue in planning for global sustainability: climate change. The scale of the problem is easily illustrated. Between AD 1000 and the beginning of the 20th century, the concentration of CO_2 fluctuated narrowly around 270 p.p.m., but now this has already been exceeded by about 30 per cent. Projections into the future suggest that, with 'business as usual', that is, a sustained increase in consumption of fossil fuels, CO_2 levels could be three times those at present by the end of the century, 2100.

Would that matter? For the past decade, the Intergovernmental Panel on Climate Change (IPCC) has studied that very question. There is empirical evidence that increasing CO_2 and increasing temperature go together: since the 1930s, there has been a substantial increase of more than 0.6°C in the average surface temperature of the earth. Based on various quite rigorous climate models, IPCC estimates that, on the 'business as usual' scenario, increased CO_2 levels will lead to a temperature increase of about 5.5°C by 2100. If it were possible to maintain CO_2 levels at around 550 p.p.m., twice the stable pre-industrial level, the average temperature increase would be smaller — which at least shows that mitigation is possible by limiting CO_2 emissions.

There is no longer much argument about the cause and effect relationship of CO_2 levels and temperature increases, although the precise form may still be uncertain. Governments first articulated their concern at the Rio conference in 1991, discussed a global plan for CO_2 reduction at Kyoto in 1996 and reaffirmed their commitment to CO_2 reductions at Marrakech in 2001, where it emerged that 188 out of 189 countries were in agreement.

The European Union has agreed to cut its emissions to 8 per cent below 1990 levels by 2008–12. Britain itself has a much higher target, yet that cut has already been largely achieved, chiefly because of the switch from coal to gas. But further reductions will take much more work as well as the implementation of new policy initiatives. You will have seen that the Royal Commission on Environmental Pollution argued that CO_2 emissions should be reduced by 60 per cent by 2050. In my view, the international community will come to realise in the next 5 or 10 years that we need even more exacting targets. The severe restrictions required to reach them will be made acceptable by public recognition of the then severe consequences of climate change.

Will emerging technology enable us to meet such targets? The Performance and Innovation Unit (PIU) in the DTI has now published its review of energy policy. In parallel with that, I led a review of energy research. We came to three main conclusions.

First, the UK is not putting enough effort into energy research. The Central Electricity Generating Board (CEGB) used to be a major player, but that effort was dissipated when the CEGB was broken up. Our level of research should be brought into line with our major competitors in Europe, chiefly Germany and France.

Second, we looked for areas where there is significant headroom between the current state of technology and what it could be. We were not aiming to 'pick winners', but simply to start the community thinking. Some of our recommendations of topics requiring more research are:

- carbon sequestration, probably in geological strata;
- energy efficiency, a 'win-win' option, but we do need more research;
- hydrogen as fuel, especially in transport. We know that hydrogen fuel cells are now quite sophisticated, but production

and storage need further research;
- nuclear energy is particularly important: we need to dispose of nuclear waste safely, but we also need to engage in nuclear fusion research;
- solar, PV, wave and tidal.

Finally, our review recommended that we should consider establishing a national energy research centre. Three of the research councils are already jointly studying the idea, apparently favourably.

I return briefly to the hydrogen fuel cell. With all the effort going into research in this area, it is not surprising that estimated costs are being reduced sharply, on the familiar S-curve pattern. In 2008, hydrogen fuel cells and gas turbines may well be competitive. Soon afterwards, fuel cells may be a viable alternative to petrol engines.

That is why we are studying in detail what would be entailed if transport switched from petrol to hydrogen. Could we produce the hydrogen without producing CO_2 as well? I am afraid that the simplest solution is to use energy from the grid. (The energy might come from additional nuclear power, which points to a quandary we may yet face.) That way, hydrogen could be produced locally, perhaps at the filling stations where you replenish your car's fuel. Of course, the economics of such a scenario need to be examined, as do the circumstances that would foster the creation of such a network.

None of this implies that we have a crystal ball. The principle underlying studies like this is that we need to keep all our options open and that, to do so, we need to pursue each of them actively. In the end, of course, the market – with appropriate regulatory drivers –will determine which processes actually come into being. The regulatory constraints are inseparable from studies of this kind. That is why my group, in advocating a national energy research centre, concluded that the centre should also consider the social and economic aspects of regulatory drivers in fostering processes alternative to fossil fuel use.

One option that does not raise the spectre of radioactive waste is fusion power. What are the prospects that it can be brought on stream? Perhaps we should be cautiously more optimistic than in recent years. The European Project, JET at Culham, has confounded its detractors by doing everything it was designed to do. The JT60 in Japan has gone further and is now producing more energy than it consumes. The next step the international community must take is to build a precursor of a power station, called ITER. The engineering design is complete; what remains is to dig a hole in the ground and build the machine.

The difficulty has been to put the act together. The European Union supports the project and also the 'fast track' version of it. So do Japan and Russia. We hope that the United States will shortly join the international consortium funding this fast track to a fusion power station.

The 'fast track' version of the scheme stems from a report a group of experts I convened put to the European Commission, which was accepted. ITER is not intended to be a commercial fusion power station, but what might be called a 'mock-up' – a test-bed within which the characteristics of working fusion power stations can be defined. A time-consuming part of that process will be the testing of the materials used in fusion reactors, which have to survive at high temperatures while being continually bombarded by the nuclear particles that are the debris of the fusion process. And that means survival for a substantial fraction of the design lifetime. So the essence of the fast track is to build a machine that will test possible materials in realistic conditions for periods up to 15 years. It is intended to construct an instrument, IFMIF, for this purpose.

The objective is to shorten the hoped-for path to fusion energy to something like 25 years. When the data from ITER and IFMIF are to hand, the designers will be able to start their work without delay. This strategy is another illustration – if an expensive one – that keeping an option open requires that it should be worked on actively. But remember that, however well this exciting programme is executed, that cannot guarantee that fusion reactors will one day generate a large proportion of our electricity. The market will be the ultimate arbiter of that.

Fusion, however, is still 25 or 30 years away. If, in the meantime, we intend to move away from fossil fuels, some simple arithmetic is helpful. Consider our present electricity supply: nuclear energy accounts for 27 per cent (24 per cent from British and 3 per cent from French reactors); renewables provide 3 per cent; fossil fuels 70 per cent.

Suppose that existing nuclear power stations are removed from the grid at the end of their lives. In 2020, the nuclear contribution to the grid would be 7 per cent (4 per cent domestic), we would have 20 per cent renewables – provided we meet the optimistic target advocated by the PIU review – and the remaining 73 per cent would come from fossil fuel. Paradoxically, despite the effort needed to generate 20 per cent of grid electricity from renewables, our dependence on fossil fuel would have increased.

So what if, instead of decommissioning nuclear stations, we replace them? (Efficient nuclear reactors are now available, such as the Westinghouse AP1000, which generate less waste per unit – or GW-hour – of electricity produced.) Then, we could substantially reduce our dependence on fossil fuels in 2020.

These figures assume that the demand for energy from the grid will remain constant. If, however, we were to attain the PIU's optimistic goal of a reduction of domestic demand for energy of 20 per cent, we could use power from the grid to produce hydrogen and thus reduce our dependence on petrol for transport and further reduce CO_2 emissions.

What all this means is that sustainability in the intermediate term depends on difficult decisions. We have to put them up for public debate before moving ahead to the longer term. ❐

discussion

Building policy. Buildings accounted for a major proportion of energy consumption. One speaker thought that most people would favour sustainable building, but not necessarily to the extent of paying for it. The consumer needed to be re-educated, and then the market would follow. Another speaker questioned the need for energy-saving buildings to be expensive. The technology used by the Beddington zero energy development was not rocket science, apart from solar panels: the use of solar energy and superinsulation made central heating unnecessary. New buildings, however, only accounted for a small part of the housing stock, and the question was what to do with the rest. One answer was that existing buildings should be retained, with intelligent refurbishment, because brick-built houses in particular represented a major energy investment.

Interconnectedness is critical to sustainability

Sarah Roberts

Sarah Roberts was at the time of this talk Manager of Global Environment and Risk at Arthur D Little, the consulting company. She has assisted some of the largest companies in the world to improve their environmental and social performance and has worked across a whole range of sectors, from oil and gas, to food, to financial services.

I am a sustainability professional rather than a scientist, although I do have a science education and a degree in chemistry. Now I mainly work for large corporations, helping them to understand what sustainability means for their businesses and how to implement it inside their companies. My topic is the relationship between science and technology on the one hand and sustainability on the other. The two are often represented as being in conflict: my goal is that they should work together.

I often encounter the complaint that sustainability is a fluffy and amorphous topic, difficult to define. Up to a point, that is so, but not because the concept is fluffy, rather that it is complex. It brings together several concepts about the way we live and their implications for the environment both now and in the future. It encompasses other people, those alive and those not yet born. Yet in one respect, it is actually very simple: it is about how we should live so that everyone can have a decent life in a positive environment, now and in the longer term.

What does that mean in practice? The World Business Council has said, "sustainable development as a process of moving towards sustainability requires a joint and long-term outlook by society that integrates social, economic and environmental objectives". So that is what sustainability is.

What is science? I shall highlight three aspects of science and technology that are important for sustainability. First, science is a systematic mechanism for studying natural events and conditions. Second, it often embodies some notion of the future and of progress. Finally, it is about solving problems or improving artifacts or systems. For me, the links between science, technology and sustainability are to do with their future orientation and the possibilities of improving the way that we live.

Many scientists insist that their work improves the quality of life, but that is not always true. On the contrary, there are deep-seated concerns about the impact of science and technology on the planet. The result has been what I think is a polarisation and a stereotyping of views. Thus environmentalists are often seen as anti-science, determined to regard science as part of the problem rather than of the solution. On the other hand, scientists often come across as either indifferent or even hostile to sustainability. Talk of how science is value-free can give the impression that scientists have no interest in the ethical implications of what they do.

The reality is that science and technology can either contribute to or inhibit sustainability. In many ways, they help to foster a more sustainable society. For example, the credibility of the scientific approach and the careful marshalling of scientific data have been crucial in establishing the case that we must change our ways, from the use of CFCs to sexual behaviour in relation to AIDS.

But there is also concern that the scientific method does not encourage researchers to study systems as a whole, yet interconnectedness is critical to sustainability. While science and technology clearly contribute to improvements in the quality of life, from health care to transportation, from new materials to steps towards more dematerialisation, science and technology can also contribute to new problems, from global warming to biological weapons.

Society ultimately decides whether science and technology are positive or negative forces for sustainability. The interactions involved are complex. Business is involved, as when it funds science, helps to set research agendas and exploits the results of scientific developments. Governments play an important part by setting priorities, providing funds, promoting research agendas and creating regulatory regimes.

The perception of science and technology by the public, the media and campaign organisations are all essential to determining the degree of trust in science and technology and their works. I shall consider a real-life example of which I have first-hand experience to illustrate how that works.

Take the furore that erupted over Shell's decision to dump the disused oil installation called Brent Spar in the sea. Greenpeace mounted a vigorous campaign and evoked a storm of publicity. Some saw the issue as a battle between science and emotion. Most analyses agreed with Shell's assessment, that disposing of the Brent Spar would have a limited effect on the marine environment and Greenpeace publicly admitted that some of its science was faulty. But, for Greenpeace, the issue was not a question of marine science but whether the planned disposal would set a precedent.

The House of Lords Select Committee report, *Science, Technology and Society*, described the affair neatly, saying that many issues now dealt with as if they were scientific involve many other kinds of considerations. Framing the problem wrongly, by neglecting moral, social, ethical and other concerns, invites hostility. Brent Spar was a classic example of that.

I sympathise with all those involved. Shell was following accepted practice in assessing the potential impact of its plans, yet found itself demonised as the worst uncaring corporation. The scientists who found themselves part of a much more complex and messy debate than they had expected also deserve sympathy. I also have some sympathy for Greenpeace: Brent Spar was seen by the public as symbolic of a wider debate over waste management and the environment.

Although there is a sense in which all the participants in the debate were losers, some positive things came out of Brent Spar. Thus Greenpeace won the war over the precedent-setting – dumping disused oil installations at sea may be permanently out of fashion. Some may believe that the outcome was irrational, but Greenpeace did at least get people thinking about the long-term impact of waste management.

The impact of the affair on corporations has been dramatic. At Shell, there was deep soul searching and quite a profound shift in the way the company understands sustainability, engages with the public and other organisations and responds to their concerns. Sustainability has become a watchword across the organisation. (I have been helping to put some frameworks, systems and indicators into place to push sustainability through the organisation.) Now Shell is one of the leaders in sustainability, not one of the bad guys. Other companies are paying attention.

Much the same might be said of the more recent debate about the potential impact of genetically manipulated organisms (GMOs), which have profound sustainability implications, positive and negative. The debate ranges over a broad range of questions — biodiversity, the environment more generally, farming practices and even livelihood and choice. The long-term implications of GMOs are still contested, but the debate has been defective in that the wider dimensions of risk are neglected, public trust is undermined and the debate does not move forward.

discussion

Species diversity. One participant was surprised to have heard nothing about the biological sciences, given that sustainability ultimately concerned life and diversity of species. Subsidies, which could be very useful policy instruments, could operate perversely, especially in relation to the fishing industry. Fish sold for a lot less than they cost to catch, and there was overconsumption of species such as tuna. Ironically, lobster were now thriving on the Newfoundland Grand Banks because the cod which used to eat them had been fished to exhaustion.

It was argued that consumption was unlikely to be reduced until population growth came down. In Italy people cried disaster when families became smaller, when in fact reductions in population ought to be applauded. Another speaker, however, thought that much could be done to reduce consumption.

Scientists should not just carry out research but should set examples as members of institutions and communities. Institutions could adopt sustainability as a policy object. Within the UK Government this was a key priority for DTI and DEFRA, the Research Councils were committed, and business was doing much more than was generally recognised.

In the corporate world, the fallout has been spectacular: Monsanto has taken from Shell the mantle of one of the most reviled companies in the world. Regulation has not caught up with fast-moving events, so that organisations take action unilaterally. In Britain, for example, the retailer Iceland was the first to decide not to sell GMO products.

We are now in a delicate situation. Commercialisation is going full steam ahead—only last month India gave the go-ahead for GM cotton while, in Britain a few months earlier, Greenpeace protesters, including its director, were arrested for pulling up GM crops. The Royal Society, in its recent report[1], summed up the dilemma very well: the debate must be informed by sound science, but science can be only one component of the debate.

To sum up, sustainability is crucial to a positive future for us all. Even people who are not much concerned about sustainability as such care deeply about the future. Sustainability is a difficult goal requiring complex interactions and an orientation to the longer term.

Science and technology have much to offer towards this goal. They can help us to understand how the world works and how to reduce our negative impact on it. The Secretary General of the United Nations has been trying to promote new studies of how research on sustainable development is used and can be improved, so that the UN can take its place alongside other organisations — governments, civil society and the private sector — focusing on sustainability.

But the contribution of science and technology to sustainability will depend on several factors. First, the kind of science that is done, which depends on things such as funding, agendas and scientists' own focus. There are strong feelings in developing countries that the Western science and technology research agenda has little relevance to solving poverty-related problems. And there is a body of opinion even in rich countries that much highly-rated science is irrelevant to their needs.

Second, is the way that science is used. Scientists cannot control the process, but they can influence it through the understanding they have of sustainability (and their commitment to the idea), the choices they make about what science they do, their awareness of the potential environmental and social implications of their work and their participation in controversial debates and difficult decision-making.

Jonathan Porritt, in a recent book on science and the environment, asked the question, "is modern science in a fit state, philosophically, methodologically, politically, to assist us in making the transition from today's unsustainable way of life to a genuinely sustainable future for the whole of humankind?" I echo his request for science that is more explicitly and purposefully geared to improving the lot of humankind and the planet.

I have three subsidiary questions for the discussion. How well do most scientists and technologists understand the sustainability implications of their work, and how can it be improved? Second, How can we increase the pro-sustainability focus of the UK science and technology agenda? Third, How can we involve the public in a more intelligent and constructive debate about controversial science and sustainability issues? ❐

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[1] *Genetically modified plants for food and human use – an update.* The Royal Society (2002).

The supplier's viewpoint

Tony Meggs

Following on from the 2001 Performance and Innovation Unit Energy Review, the Energy Policy Energy Policy White Paper is due to be published in early 2003, setting out policies for the next 10 years. At an FST dinner/discussion meeting on 25 July 2002, three speakers aired their views on energy policy. The discussion that followed is summarised by Sir Geoffrey Chipperfield.

Tony Meggs is Group Vice President of Technology at BP. Mr Meggs has global responsibility for technology strategy and performance, and procurement in BP. Before that, he was a Group Vice President in BP's exploration and production business. He read Natural Sciences at Cambridge and went on to study petroleum engineering at Imperial College.

I shall talk about energy policy from a supplier's view and make four points. First, energy is a global commodity and all policy decisions need to be seen in that context, especially when considering security of supply. Second, oil and gas are going to be around for a long time to come, although the balance is shifting towards gas — a good thing from an environmental perspective. Third, total energy supply is the real issue for the foreseeable future: we at BP believe that renewables are an important part of the future but, until they become viable, other ways of managing carbon emissions will be necessary. My fourth point, as a technologist for BP, is to say that technology will always continue to surprise us, usually in positive ways.

I begin with world energy supply and demand. We tend to talk a lot about transportation, but that is rather a small part of total use; approximately 25 per cent, which is largely met by oil. Industrial and similar activities account for about 40 per cent of the total usage of energy (and 80 per cent of this is in the form of fossil fuels). Electricity generation is where coal retains a significant share of the market. Energy supply and demand will continue to grow.

In the global fuel mix, gas will continue to grow more rapidly than oil; for many years it has been growing about twice as fast and we believe that trend will continue. (Transportation innovations have made it a global fuel.) Nuclear generation, on the other hand, will flatten out as existing plants are shut down. Renewables, even including the use of wood, are a rapidly growing but still relatively small proportion of the total. There are many possible scenarios for the future but every one of them contains a significant proportion of oil, gas and coal.

Technology has played an enormous part in maintaining oil and gas reserves and the reserve to production ratio. There are now 40 years' worth of oil reserves in the world, as there have been for several years; we continue to find as much or more than we produce each year. With gas there are at least 60 years' worth of reserves, even though gas has been explored for much less than oil.

I now turn to the UK industry. The North Sea is typical of oil basins throughout the world. Actual production has far exceeded the original forecasts. Already we have taken about 20 billion barrels of oil out of the North Sea, more than twice what was originally thought possible. In the Forties field we predicted a recovery factor of 40 per cent, but now we expect to recover more like 70 per cent of the original oil-in-place. And there is oil for many years to come, although we believe that production is now at its peak, declining slowly over time.

Technology has contributed enormously to improved recovery – techniques such as 3D seismic imaging, cheaper and smarter drilling, smaller and lighter facilities and the ability to gather information from wells remotely. At the same time, North Sea oil has created an enormous skill-base here in Britain. I know of no oilfield in the world with more than a billion barrels left in it that has ever stopped producing. That is why North Sea oil will be around for a long time to come.

Technologically, this is a very exciting time in the oil business. The new techniques have produced a new understanding of what happens underground, allowing the possibility of much higher recovery. It is a quite unusual confluence of technology.

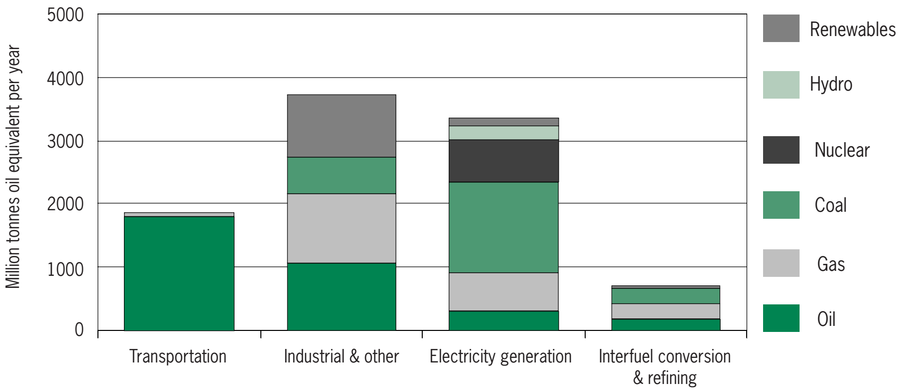
Optimism apart, the British North Sea now consists of fairly small fields and therefore is one of the more expensive basins. In a world where there are lots of other opportunities, it is important that the conditions for developing those fields remain right, fiscally and otherwise.

Moreover, although Britain produces 75 per cent more oil than it consumes, it is also an importer. We export about 80 per cent of production and import about 65 per cent of consumption. That merely demonstrates that oil is a global commodity and that the meaning of self-sufficiency is modified by the global market.

I now turn to gas, which is a success story. The recent shift to gas in Britain has been a good thing because it has reduced CO_2 emissions substantially. We share the view (see Wright, page 13) that in 2005 or thereabouts, demand will exceed supply. But there is an enormous amount of gas in and around Europe: 70 per cent of all of the known gas resources in the world can be accessed economically from there. There is enough to last at least 150 years and that is just the gas that we already know about. The issue of quantity is not in question.

Will the infrastructure be built to retrieve this gas? History suggests that when commercial opportunities arise, the required infrastructure is built. But stable

WORLD PRIMARY ENERGY SUPPLY



Total primary energy supply = 9640 MMTOE/YR

Source: OECD/IEA World Energy Outlook. Data for 1999. © OECD/IEA, 2002

supplies into the future will also require such things as the harmonisation of quality, liberalisation of European markets, access to pipelines and some attention to standards.

There is another important question we must face. The major sources of gas are on the periphery of Europe, in North Africa and South-East Asia, for example. What if the countries concerned set up a gas-based equivalent of OPEC? From my own experience of selling gas from Algeria into Europe a couple of years ago, there was much anxiety about what appeared to be a unilaterally imposed (by the EU) mechanism for selling gas, with unwelcome consequences. As the EU develops its liberalised market in energy, it is crucial that there is a healthy dialogue with the producing countries.

More than 25 per cent of gas crosses international boundaries and this proportion is increasing all the time as costs are being driven down quickly by technology. There are also novel opportunities — floating offshore liquefaction facilities, for example. There is a wealth of opportunity yet to be realised. We are early, I would say, in the lifetime of the gas resource, which is relatively environmentally benign.

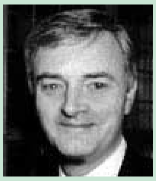
I should mention a couple of other pieces of technology. There is a great deal of work going on, in which BP is involved, to find ways of using fossil fuels, particularly coal, to produce hydrogen and to sequester the CO_2. Success could even make coal a clean fuel of the future. Various schemes are being studied, but all ultimately depend on storing the CO_2 underground. Putting CO_2 into depleted oil and gas reservoirs could even enhance recovery and provide geological disposal of the gas. Perhaps we should not abandon too many of our North Sea platforms in case this technology proves to be viable and cost effective.

I want to talk briefly about renewables, particularly solar and wind, which we regard as the major contenders. BP has a large and growing solar business – we are one of the largest solar manufacturers in the world. The economics continue to improve, although it is still expensive. Solar only really competes in the retail market and, right now, requires some form of customer incentive to be viable. But we estimate that, in the next 5 to 10 years, it could be competitive at the top end of the market. But there is enormous room for growth and, again, technology may surprise us.

Wind is a different story. It already competes in the wholesale market and I think that by 2005 and beyond we will see wind being generally competitive. So there will be growth in renewables, but really significant generation will take many years to develop. Meanwhile, carbon capture may be the means of transition from a hydrocarbon-based world to the very distant future when renewables carry the load. But we should not forget that technology will continue to surprise us, usually in positive ways. ❐

Energy demand 30 years from now

Professor David Fisk CB FREng



Professor David Fisk is Royal Academy of Engineering Professor of Engineering for Sustainable Development at Imperial College and Chief Scientific Adviser at the Office of the Deputy Prime Minister. He was previously responsible for the development of UK Climate Change Policy, including negotiating the Climate Change Convention and its Kyoto Protocol.

Energy efficiency is dealt with in the report[1] of the Performance and Innovation Unit (PIU) conventionally, largely relating to the near term. I propose to complement that approach by focusing on energy demand 30 years from now. I will argue that the nature of the demand for energy will then be very different, and will be matched by radically different technology.

About 20 per cent of European energy consumption can be described as tightly managed. To entities belonging to this “20 per cent club”, which naturally includes energy producers, energy is a significant operating cost. What we call energy policy is largely about investment decisions in this sector, which has the unfortunate side-effect that energy efficiency is naturally cast in terms appropriate to the 20 per cent club and is frankly inappropriate to the remaining 80 per cent.

In the PIU report, energy efficiency is indexed as an attractive but elusive rate of return on capital. The more appropriate tool for the unmanaged 80 per cent is a different branch of economics, innovation theory. In what follows, I shall assume that future energy efficiency in the 20 per cent club is well catered for by the PIU analysis and that efficient energy pricing, the *sine qua non* of the approach, remains the bed-rock of future policy. So what of the remaining 80 per cent?

There seems no problem in analysing energy efficiency with the tools we would use to analyse any other consumer product. Two important elements are required to construct an innovation economics picture of future energy demand. First, we must understand the aspirations that create the motives for change, then we must understand the constraints caused by the natural diffusion path for innovation.

I begin with the assertion that energy consumption by the 80 per cent is a 'positional good' as defined by the American economist Thorsen Weblen. Such a good is one whose ownership or consumption confers a confirmation of position, status or vanity: you feel better, the more you show you have of it. Until the 1930s, energy was a more normal 'intermediate good', meaning that you feel richer if you are able to use less of it. If my proposition is true, current forecasts of energy demand, based on current usage patterns, incorporate positional good behaviour.

The innovation path for positional goods is easy to follow, from introduction at social class A to final adoption by social class D. In the prosaic world of the 80 per cent, it is also easy to see from where the innovations must come. Servicing innovations in the domestic market is expensive because the buyers are diffusely spread geographically and the information chains are weak. Innovation theory emphasises that the highest probability of success in turning invention into product is an informed first customer. So the high technology solution to an energy efficiency problem almost invariably starts in the industrial sector.

Think energy, think fur coats!

The PIU analysis and its consultations were influenced by a target for CO_2 emissions proposed by the Royal Commission on Environmental Pollution of a 60 per cent reduction. This in turn was predicated by recommendations of the IPCC aimed at avoiding more than a 2°C rise in global average temperature. Many of those consulted thought the target 'challenging'.

If energy modellers used innovation theory a little more, they might not be so reticent. Consider circumstances in the year 2030 on this 'challenging' scenario. Global climate models will then be part of life, not black boxes run by researchers. They will be regularly used to predict near-term seasonal climate likelihoods. The world's citizens will use them to change the crops they plant, charges for bad weather insurance or the holidays they plan. 2030 is a world in which global warming is both real and, in the physical sense, predictable. This is not a comfortable position for a positional good. Think energy, think fur coats! When that happens, part of the underlying demand model in the IPCC scenarios becomes invalid.

I am going speculate on the science and innovation consequences for two key sectors of the 80 per cent — buildings and transport. The impending switch will bring in a host of exciting technologies and changes in economics and behaviour.

discussion

Gas danger. A member started with a brief analysis of the difficulties lying in the way of achieving RCEP CO_2 reduction targets and the dangers of relying so heavily on gas – 63 per cent by 2020, 80 per cent of which would be imported. Trends showed that electricity prices would remain low over the next decade- largely because of existing capacity – with generation fuelled by 80 per cent fossil fuels. Could a competitive market deliver low prices and diversity? Could it ensure security of supply? How were renewables to compete?

Buildings in 2030

There is a myth that buildings are a slow-response part of the changing energy demand picture. In primary energy terms, something like 30 per cent of energy consumption by buildings has a half life of less than 5 years, 60 per cent less than 10. (Only bad design shuts off options at these change points.) These half lives mean that innovations entering from industrial applications around 2020 will have very good market penetration by 2030. I will now look at some contenders.

"Natural buildings" will not work in every part of the globe. Removing humidity is a West Atlantic summer problem, not an East Atlantic problem. So unless Europeans in 2030 want to live in a Manhattan-experience theme park, there will be an incentive for designers to rediscover natural design. Here are some key technologies.

The photovoltaic (PV) is a good example of an industrial technology entering the top end of the A-D chain in buildings. A photovoltaic roof on a Californian mansion is the homebuilder's equivalent of a Rolex. And as a Californian you are buying front-edge technology.

Anticipating how that technology will filter down the A-D chain tells us that the important properties of a solar collector are not necessarily its collector efficiency — that is 20 per cent club thinking — but whether it can be substituted for existing building cladding. There is some real material science to be won here. The A-D model tells you that installing PVs on social housing roofs at the beginning of the market is death: patience is a better low-energy social housing policy.

The implication of PV, repeated in many other developments in building services, is that buildings in the 80 per cent group are going to be both energy exporters and importers. Some countries already operate tariffs that simply charge for the net electricity take.

Although a theoretical limit of 20–30 per cent efficiency is often given to PV, we should not forget the solar collector technology, with 200 per cent efficiency. If the term had not already been trademarked we would have called it 'windows'. Daylight offsets inefficient lighting and air conditioning load, the problem is that we have rather lost the Victorian (or for that matter 12th century) skills to design real windows, as opposed to glass squares.

The current design techniques date back to Hopkinson's work on glare in the 1960s and have not taken on board much that we have since learned about the visual system. Expect a sea change in the hole in the wall when modern optical perception theory rejoins window design. Also, we should not forget the extraordinary advances made in optical fibre technology in the 1990s and what they might deliver for lighting interiors.

A building's curtilage stores an extraordinary amount of energy. Admittedly most of that is in stationary pieces of iron in the garage, but low-grade energy is also stored in the building fabric and services. Once electricity suppliers find themselves with a market of actively managed net consumers, that storage capacity becomes intriguing for grid management. Computerised building management systems could, like their computer counterparts in the City that automatically trigger deals in stocks and shares, find storage capacity automatically, particularly with electrical devices using power-line signalling. The power engineering of these connections is a brave new world. The availability of storage, virtual or otherwise, is of course the big economic issue for some renewables.

Walt Patterson at the Royal Institute of International Affairs (RIIA) has upset everyone by suggesting that the electricity network optimisation model might actually invert and the grid become a friendly standby. The key point is about economies of scale, but new turbine technology invites us to think again. A new miniature turbine can be fully serviced in a day, a large turbine may take a month. A set of small turbines can follow load without spinning reserve and all the other complications for the high voltage engineer. This also encourages us to suspect that combined heat and power technology might be revisited, not as use of waste heat from power generation but as use of the generation of electricity from spare combustion capacity.

Considering that, in the 1970s, the CEGB was exploring the possibility of liquid-helium cooled superconductors to reduce transmission losses, why are we apparently indifferent to superconductors at liquid-nitrogen temperatures? The problem is not, I should emphasise, the losses in copper wires that would be displaced if room-temperature superconductors were a reality, but that it would be possible to store electrical energy or to maintain magnetic fields without energy loss. Overnight, the components of electricity demand would be radically recast.

discussion

Investment in renewables. A persistent concern was the problems facing the development of renewables on the scale necessary to meet RCEP targets for CO_2 reductions, unless nuclear was seen as a major energy source. Investment in renewables would not take place unless the market was there to support it; on the other hand the market would not develop unless there were the goods available at commercial prices. Was government action needed to stimulate the market or support investment ahead of market growth? One member saw a bleak future for renewables, because history showed that since 1810 we had exhausted the ability of land surface to take further use. This view was strongly rebutted by other members who said that the key component in developing renewables was new and innovative technology which made use of natural features, such as sun, waves and wind, which had not hitherto been exploited.

There was concern that the take up of plants to burn waste for energy had been slow – they solved the problem of an energy source, but also of dealing with waste. Biotechnology research had a part to play – the development of new forms of yeast to use waste, and algae to generate hydrogen.

Much of the energy consumption in Western European buildings is a consequence of external factors whose future trends fortunately correlate well with the lower demand projections of the non-positional good model. Office equipment power loads are falling. More efficient screens and PC hard drives are coming onto the market. Traffic noise and traffic air pollution have driven us to live inside sealed buildings, but the latter certainly and the former quite probably will disappear by 2030. As with the CEO's tif screen, these are product developments that do the job better.

Transport

Some of the changes I signalled in the building sector could help reduce journey requirements. In 2030 it would be surprising if we were not running on twice our current fuel efficiency. The private car has been a classic positional good since it took over from the horse and carriage. Most major innovations began in an industrial context (quite often Formula 1 racing) and percolated down the A-D chain. Fuel efficiency technology has a market pull but, if you subscribe to the innovation theory approach in the context of increased range (or extra storage space), it cannot be at the expense of performance. This is why manufacturers are exploring exotic high-performance solutions such as fuel cells although battery technology is already available.

Innovation has meant that vehicles have become less and less purely mechanical. ABS has already percolated down from the top, fly-by-wire technology is almost here. It is not far fetched to see hybrid electric engine technology as a contender for high-efficiency 2030 technology. The point is to use the engine at optimum output and not to use expensive gears or brakes to control it. Apart from range (which nearly doubles over today's internal combustion engine), the great advantage is quiet running and increased reliability, not to mention reduced emissions.

Another issue that may change vehicle technology by the 2030s is that of energy security. Two considerations are central. The first is that, over the past two decades, oil has become the strategic fuel in the economy. If there is a shortage, we find that it is not just doctors and surgeons who need petrol coupons to get to work, but the hospital's nurses, porters and boiler men who now live equally far away. Road transport powered by oil carries the bulk of goods, even to the rail marshalling yards.

Unlike electricity generation, transport fuel is not diversified. Kerosene, petrol and diesel all come from the same feedstock. About 65 per cent of the world's oil is now produced in the Middle East, where reserve to production ratios easily outstrip those in other parts of the world. So the 65 per cent can only increase, not decrease.

In 2030 most of the world's oil seems destined to come from the Middle East. It is not far fetched to see diversification of fuel types in transport as a European consumer strategy. Without fuel diversity, after all, energy efficiency is of little help in a supply crisis. So is there a parallel technological route? This might be achieved in the refinery by drawing on other sources of hydrocarbons. But if the hybrid car has introduced the electric drive chain, that is fuel diversification of a kind. Re-engineering the supply of electricity to the traction source is a really exciting area.

We have been trying to make electric vehicles for a century. Milk floats are not generally seen as leading-edge transport technology. The energy security issue might change the model. Indeed one of the first hydrogen-powered cars on the market is dual fuelled, just like the old coal/oil power station. The fuel cell is already available for stationary generation of power, with some fuel-cell models soon to enter the US car market. The whole surface transport market would not be hydrogen-powered, but different technologies would be spread over the A-D range.

While we sometimes bemoan national short-termism, it is strange how sensitive people can be to stories about futures a whole generation away. The Royal Institute of British Architects is going to be upset because I said that natural buildings will predominate in 2030 and the RAC Foundation will be upset that 2030 cars won't need drivers or breakdown services. But none of this will happen tomorrow.

Few would disagree that we are moving into a transition in energy that is only hinted at in the PIU consultations. What I have tried to demonstrate is that energy efficiency, rather than just having a part to play, may well be the dominant new technology in the future. And for 80 per cent of the market it will not be because it offers a good rate of return, but because efficient systems will be that much better in a world where conspicuously wasting fossil energy is a mark of bad taste, not comfortable affluence.

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1. Performance and Innovation Unit *The Energy Review* DTI (2001).

Questions for the White Paper

Rob Wright

Rob Wright is joint Director of Energy Strategy and Director of Coal Policy at the DTI. He joined the Civil Service in 1975 and has worked also on secondment to the governments of Canada and Hong Kong.

I intend discussing both supply of and demand for energy in the context of the forthcoming energy White Paper. *The Energy Review* by the Performance and Innovation Unit (now renamed the Strategy Unit) has been followed by full consultation on its conclusions over four months ending only in mid-September [2002]. That is one reason why I cannot tell you what will be in the White Paper we intend to publish around the turn of the year.

We are aiming to develop policies for the next decade against the backdrop of the next half-century – a nearly impossible task. One difficulty is to strike the optimum balance between three particular objectives: security of supply, cost and the environment. All these pull in different directions. For example, excess supply provides resilience, but costs a lot. Diversity of supply also provides resilience — but we have some worries that a purely market approach to energy will not deliver the degree of diversity that we might need. Renewables provide us with new opportunities for electricity generation, but if they are largely wind-based we are going to have problems on calm days. So there are questions about security too.

On cost, competition is clearly good and has delivered important savings, notably in the wholesale price of electricity. But will those prices stimulate the investment likely to be needed as well as the diversity required in the longer term? On the environmental side, to the extent that renewables do not produce CO_2, they are good, but some environmentalists hold that these benefits are offset by visual impact; there are also difficulties about costs. Nuclear generation is clearly good in one environmental sense — no CO_2 — but bad in another (and will be until we know what to do about nuclear waste).

There is no easy or even correct answer. The challenge in what we are trying to do is to balance conflicting considerations. I shall take each of the three components in turn.

First, the environment. We have taken up the RCEP challenge to put ourselves on a path for a 60 per cent reduction of CO_2 emissions by 2050. We have to take climate change seriously. Action is necessary. But the energy system cannot do it alone. No doubt energy efficiency will be further improved. We might be able to get up to 20 per cent of electricity generation from renewables. But even with totally carbon-free generation, there would still be a big gap between actual emissions and the RCEP target has to play a part in meeting the target.

We cannot ignore the present contribution of nuclear generation to keeping down CO_2 emissions. That will be attenuated as nuclear plant is taken off stream in the coming 20 years. The PIU said that it was essential to keep the nuclear option open. We are now working on precisely what that entails. It is clear that the White Paper must reach a conclusion on the issue, but it is too soon to guess what that will be.

Security of supply is another consideration. North Sea gas is in decline and Britain will be a net importer of gas by 2005. The work we have done suggests that, by the winter of 2004-05, there may be a shortage of gas in Britain. We are not yet in panic mode because the market will adjust if the prediction appears correct. If, on the other hand, projected investment is seriously delayed, we may have some gas problems.

Whatever happens, a large increase in the use of gas in electricity supply is projected. Imported gas is destined to be an important part of our energy mix. One of the questions the PIU did not tackle is

continued on page 24

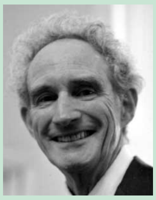
discussion

The nuclear question. While it was asserted that the use of nuclear was inevitable, it had to be acknowledged that the public did not accept this and how to deal with the issue would be a major problem for ministers in the White Paper. Unless they could conclusively demonstrate, first, that the RCEP target must be met and, second, that even allowing for the most optimistic rate of growth for renewables and the most sanguine hopes for energy efficiency, it would not be met, then they could not hope to convince public opinion that nuclear was the only solution. The first hurdle could be overcome only by a sustained public campaign, which had not yet started; the second meant proving a negative, always difficult. It was no answer to say that the French did it, why can't we?

Science, technology and engineering in society

The Lord May of Oxford OM AC PRS

On 25 June 2002 the FST held a dinner discussion to debate the relationships between science and engineering, and their relative roles in society. During the discussion that followed, representatives of science and engineering spoke on the theme of how science, technology and engineering can work more closely together to solve problems faced by society. The articles that appear here are edited from verbatim transcripts of the evening.



Lord May became President of the Royal Society in 2000 but still maintains an active research programme as a Professor at the Department of Zoology at Oxford. From 1995 to 2000 he was Chief Scientific Adviser to the UK Government and Head of the Office of Science and Technology. He was elected a fellow of The Royal Society in 1979 and is a recipient of the Order of Merit and Companion of the Order of Australia.

I will be tackling three questions. How should the UK research and technology base respond to interdisciplinary questions, are the new institutional structures succeeding in breaking down traditional barriers between disciplines, and how should science, technology and engineering research and innovation be organised in the UK?

First a little history. I learnt recently, to my embarrassed surprise, that the British Academy, the sister academy to the Royal Society, was spun out of the Royal Society as a result of discussions in 1899. I look at that rather ruefully, because my personal preference would have been to take the other route discussed at the time, that of widening the compass of the Royal Society to include the humanities; not just looking at science, engineering and technology but putting in the arts and humanities. I have always believed that there is only one culture, not two.

What the Royal Society, engineering academies and technological academies are about is understanding and using that understanding in the external world. The arts and humanities are about understanding our place in the external world, so I see it as a wider continuum and I personally would like to see the Humanities Research Board brigaded along with the other research councils—*a fortiori* therefore, I see the Academy of Medical Sciences and the Royal Academy of Engineering as part of this seamless continuum.

It is interesting to look at other countries. Australia, for example, has an Australian Academy of Sciences, which has broadly the breadth of the Royal Society, going from medicine to engineering. Then there is the Australian Academy of Technological Science and Engineering, which is broadly the parallel of the Royal Academy of Engineering. In the United States there is the conjoined triad of the National Academy of Sciences, the National Academy of Engineering and the Institute of Medicine. The boundaries between the US institutions are a bit sharper so there is less overlap and the three of them co-own the National Research Council. However, it is true that, as the National Academy of Sciences is the oldest (it was started by Abraham Lincoln) and biggest, it tends to be the first among equals in that its President tends to be the CEO of the National Research Council.

Personally, I find all this boring, much of it driven by the human vanities as much as by anything else. The unity of all these institutions is far more important than their differences and distinctions; they are all dedicated, one way or another, to the rest of the phrase that originally characterised the definition of the Royal Society of London when Charles II and others started it, they are all “dedicated to the pursuit of natural knowledge and its applications”. There are, of course, boundaries of various kinds and I think that the problem, insofar as there is a problem, is to promote cooperation and de-emphasise those boundaries.

Interdisciplinary problems

Can the UK research and technological base respond to interdisciplinary questions? My answer is that we seem to be better than most in taking an interdisciplinary approach to research—but even we could be doing better.

The facts that I would bring to bear on this matter are highly imperfect, but nonetheless better than repeated assertion, and they are to look at the bibliometric base of some 10 million papers, 100 million citations in science, medicine and engineering. These are lumped together, for one set of uses, by the Institute of Scientific Information in Philadelphia, into 21 rather arbitrary boxes. Some of these boxes are for sensible things like physics, chemistry and clinical sciences, and left over is a 21st box, which is a grab-bag of things that nobody quite knew what box to put them in, called ‘multidisciplinary’. So let us just assume, and it is not ridiculous, that the multidisciplinary box does say something about multidisciplinary studies. We can now compare the UK with the world average in this classification using the average citation per paper. We in the UK do above average in nearly all of the 21 categories in the ISI database, and the one we do best in is this box called ‘multidisciplinary’.

You could also ask about relative investment in these disciplines, that is a quite different question. What is the fraction of the UK papers that are in that box, compared to the fraction of the world's papers in that box? Of the 21 different units, it is the multidisciplinary where we are significantly above average in our investment input. I yield to no-one in my ultimate contempt in these bibliometric measures. But these statistics—imperfect though they are—do appear to tell us that the UK research and technological base responds to interdisciplinary questions rather better than most others.

On the other hand, that question is often asked in connection with the research assessment exercise where a truth created by repeated assertion is that multidisciplinary things suffer. A Higher Education Funding Council for England (HEFCE) study looked at things classified as multidisciplinary and decided that they did no better and no worse than the average in other subjects, thus concluding that they didn't suffer. But I have just suggested that other forms of analysis suggest that we are relatively better at, and invest relatively more in, multidisciplinary things. Therefore, if they are treated even-handedly, they ought to have done better than the average in the RAE exercise, so there is an argument that suggests 'yes, there is a slight penalty and we could do better'.

discussion

Education. While a principal theme in the discussion was the effect that different professional requirements in the tertiary sector might have on the ability of scientists and engineers to promote and develop multidisciplinary activities, many speakers echoed the points that the initial problem was getting students to undertake scientific and engineering studies at all. Speakers stressed the poor quality of teaching in science and mathematics, but there was also a marked contrast between biological and physical sciences – the former were much more popular, and much better qualified teachers had taught applicants. The key was getting scientifically qualified teachers into schools. But, given the indiscipline in schools, the low status of teachers, and other opportunities, why would any scientist want to teach? Only, perhaps, if they experienced teaching and discovered the satisfaction of opening and developing young minds. Thus Sir Richard Sykes' scheme for getting young scientists into schools to teach for a period without committing themselves finally was warmly to be welcomed.

A further problem was the poor quality of career advice in schools – one speaker said that advice had been given that universities would be less likely to accept science and mathematics students than other subjects.

Breaking the barriers

The second question: are the new institutional structures succeeding in breaking down traditional barriers between disciplines? If you look at our academies, about 10 per cent of the Fellows of the Royal Society are also Fellows of the Royal Academy of Engineering, and 10 per cent of the Fellows of the Royal Academy of Engineering are Fellows of the Royal Society. There is a fair amount of overlap, across a huge continuum. The Royal Society is very ecumenical, covering medical science through all shades of the life sciences to the physical sciences and engineering. It differs from the Royal Academy of Engineering and the medical Royal Academies is that it tends to emphasise academic research into the basic understanding of medicine and engineering, whereas the professional bodies properly emphasise all manner of practice and application. But we are more ecumenical in those overlaps than most other countries' corresponding academies.

I am very up-beat about the Engineering and Technology Board (ETB), set up in response to findings presented by The Hawley Group, a task force chaired by Dr Robert Hawley, Chairman of the Engineering Council. The ETB will be a powerful force in working against what I believe is a pernicious trend of creating boundaries and divisions and little specialisations and Chartered this, that and the other thing, making undergraduates choose their areas of specialisation far too early.

The ETB is wisely heading in a more ecumenical direction that actually reflects the fact that, in organising curricula, the one thing that you can say for absolutely sure in science, in engineering, in technology, in medicine is that whatever is in the curriculum today will be a great deal different from what is going to be the practice of the people who emerge. For that you want flexibility.

Innovation

Now for the third and last question—how should science, technology and engineering research and innovation be organised in the UK? My answer to that question is 'with a light hand'. But, in a bit more detail, how should they be taught? I am asking whether they are introduced at kindergarten level, much less primary, secondary or tertiary; they should all be taught as enterprises that are primarily questioning, experimental, problem solving compared with the endless lists of facts that characterise too much of the syllabus and the over-examined implementation of it that we have been saddled with.

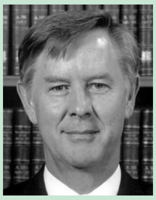
I also go further. I believe that we will do well to emphasise more at every level, both in training and in practice, the role of the scientist, engineer and technologist as a citizen. Each is a profession with an ethical dimension, and the curricula in science, engineering and technology need to go beyond a broader interpretation of this into enquiry and the acquisition and application of natural knowledge into the recognition that the application itself has questions that engage the public more widely. Frankly, I think that that kind of flexibility is going to be harder, in many ways, to teach. But at the same time it is my belief that, if we can succeed in moving in that direction, we will do a great deal to cure the problems of recruiting younger people into science, engineering and technology.

Someone once said that there are two kinds of people, those that divide people into two kinds, and those that don't! But more generally, there are splitters and lumpers, there are people who want ever more finely to split the taxonomic divisions and there are those who want to look at things more broadly. It is my view that engineering, science and technology should all be aiming to represent and, indeed, to evangelise the highest standards of enquiry into how the natural world works and into applications of that knowledge for the common good. In particular, the Academies of Engineering and the Royal Society, since their inception, have been much engaged in what we call science in society. The expression of that engagement has changed hugely in the past couple of decades and will continue to change.

Today our academies work together and will continue to do so in the future, sometimes separately, sometimes together. The recent influential joint study on nuclear energy and the future climate, for example, has a part to play in discussions about how to seize the opportunities offered by advances. ❐

Science and engineering: the industrial perspective

Sir Peter Williams CBE FRS FREng



Sir Peter Williams is Chairman of the Engineering and Technology Board. He is a former Master of St Catherine's College, Oxford and President of the British Association for the Advancement of Science. In 1985 he was appointed Group Chief Executive of Oxford Instruments and finally stepped down as Chairman in 1999.

We have been asked to look at the differences, if any, between an engineer and a scientist. The brief sounded like the cue for a joke: if the scientists ask the question why, and the engineers supply the answer how, why is it that the accountant always wins? Because he is the one who says how much!

I approach the question from the standpoint of an industrialist with 25 years at the sharp end in manufacturing, in high tech industry. In the industries that I have been involved in, there is—to echo Bob May's phrase—a continuum of skills, all the way from the very fundamental research in the R&D laboratories to the production engineers on the shop floor. My personal bias therefore in the debate about engineering and science is that they are more alike than they are different and, indeed, that the three contributors to this discussion are more alike than different.

From the industrial standpoint, engineering and science are essentially synonymous. Take magnetic resonance imaging (MRI) as an example. MRI was invented by a physicist, Peter Mansfield. John Mallard of Aberdeen worked on it, but it was Mansfield, with help from his medical friends at Nottingham, who dreamt it all up. Once the process underwent industrialisation the project became global, with Toshiba, General Electric, Siemens, Phillips, Hitachi and the company that I worked for, Oxford Instruments, all involved.

At Oxford Instruments we were asked to build magnets. MRI is all about encasing a patient in a magnetic field. We made magnets for other purposes. Think about what that entailed for a small company. For a start, the magnets that we made were based on superconductivity, so you had to have a physicist who understood what superconductivity was all about. To build a magnet, you need a good materials scientist to make wire to pass the super current. This is a black art I can assure you, and there are not many of those people around. When you wind a wire into a helix and pass a current through it, you get a force. So you need mechanical engineers who understand the properties of solids under stress at 4 degrees Kelvin where there is no database in the handbook or anywhere else. You need electronic engineers to tell you how to control it, you need marketing people to sell it, and you need the medics all the time looking over your shoulder to tell you whether you are going in the right direction.

If that isn't interdisciplinarity and multidisciplinarity, I don't know what is. From personal experience, working for nearly 20 years on MRI, by the time we had been working together for a few years, we were virtually indistinguishable—you could not tell the physicist from the materials scientist from the mechanical engineer. We had fused into a team. The team seems to have got the right answer because Oxford Magnet Technology is not far short now of having shipped £2 billion worth of MRI magnets—£2 billion over 20 years is not bad going. So I betray my bias, I am essentially a 'continuum' man, I believe that engineering and science merge and we are merely looking for subtle distinctions between one extreme of the continuum and the other.

What do we need?

If you believe that, essentially, the supply of scientists, technologists and engineers is simply the supply of the continuum of different types of the same thing, you can start by asking some very simple questions. What does society and what does the nation need? What does industry itself believe that it needs? Then the most intractable question of all, what do the individuals want? This is a free society, one in which government does much but it does not attempt to tell us how many chemical engineers we should produce or how many low temperature physicists. It allows some semblance of market force to operate. I think that we all know what it is that the nation needs from its scientists and engineers from the industrial perspective. Industry's needs are equally straightforward—trained manpower, a flow of ideas, supply of capital. And of course, industrialists will tell you in the present era, the right currency rate and a business friendly taxation environment. So what the nation ostensibly needs in economic terms and what industry says it needs in detailed human terms are relatively quite straightforward.

But then you get to the difficult bit and this is where I am getting towards the Engineering and Technology Board. You

discussion

Multidisciplinarity. There were still difficulties in the tertiary sector in promoting multidisciplinarity. There was, for example, the gap between physical and biological scientists. This might be traced back to a fundamental difference between the lineal and hierarchical structure of mathematics that requires a long background of teaching, compared with the more immediate descriptive structure of biological science, but there was no reason why the two sciences could not learn more from each other. Some speakers thought that there was an inherent problem in universities focusing on teamwork, because there were difficulties in examining on it, and it was impossible to reduce the content of individual science courses without risking failure to get accreditation. There was also the danger of getting breadth without width – of dumbing down. Other speakers said that it was possible to examine and accredit at team level; but, more important, if it were right to teach multidisciplinary themes and work, then they should and must be taught.

Universities had one great advantage – they had (even if not enough) irreverent and experimental young who made a culture of innovation and cross-fertilisation more likely. Research money should therefore go either to them or to industrial research departments, which were focused on solving problems that were barriers to commercial success. Research institutes were not the answer; the dangers of middle-aged consensus and lack of focus were too great.

What lay behind the call for multidisciplinarity was the view that rigid professional structures and training inhibited innovation and development. But barriers and lack of understanding between the different worlds of academia, industry and the City were equally inhibiting. Scientists and engineers should be encouraged to carry their experience and knowledge across these worlds. This meant not only devising much more flexible career paths, but also developing respect and understanding in each of these worlds for the value and achievements of the others. There must be no more suggestion that scientists who go into industry are ‘selling out’.

can take a horse to water— in this case you can take young people through primary, secondary and tertiary education— but we all know that it is a free society with a freedom of choice. We are saturated with numbers, but the numbers that stick in my memory are, of course, the A-level applications in mathematics, physics and chemistry on the one hand and the enrolment figures in our universities and colleges of further education, in subjects such as engineering, chemistry and physics on the other. Gareth Roberts’ report, which ought to be a bible for everyone here, paints a very stark picture.

Although the national need is clear and although industry’s need, and its ‘Open for Business’ signboard is up and clearly visible, the young are voting with their feet in alternative directions. I wonder where this problem originates from because, with another hat on, I have had the great pleasure over the past seven years of chairing the Science Museum. I took a Minister in there, deliberately over half term, recently and it was teeming with children. The school parties of 5, 6 and 7 year olds were queuing up to get in, buzzing with excitement about engineering, about science, about technology, the interactive displays, the whole 9 yards. Then why do we not see A-level and tertiary education statistics that mirror this enthusiasm? Are we guilty of giving out mixed messages?

Two cultures

Bob has commented on the famous CP Snow ‘two cultures’. We still force two cultures on our children aged 16. We ask ‘do you stand for humanities or the sciences?’ Those of you from what you would describe as the engineering side of the house tonight, although there are no sides, would say ‘why is it always just the sciences?’ But there it is, the sciences and engineering. When youngsters look beyond that choice, they see mathematics looming as a challenge for them and, boy, do we all know about the problems that AS level mathematics is inflicting on our children! They look beyond education, they look at the professions that they may become part of, they see fractured professions, they see multidisciplinary and individual disciplinary bodies in great profusion. They look at universities and the range of choices of courses and again they see a huge disparity in offerings.

Look at the images of industry, particularly of manufacturing industry, less so services and bio-pharmaceuticals. If you graduate as an engineer you will, along with applied scientists, end up in a community which Bob Hawley and Bob Malpas identified as 2 million strong. Two million people practise science and engineering for a living in industry, but you will find only half a million are members of professional engineering institutions. You will find only half that number are Chartered Engineers and if you look at those who are still practising, as opposed to retired or overseas, you will see that a bare 160,000 have survived in the engineering profession.

Are you confused by what I have just said? I am; we are all confused. Fortunately, I am lucky because when Bob Hawley tapped me on the shoulder last October he said that the disciplines of engineering had clearly recognised these issues. The problem of regulating the engineering profession has been separated from the old Engineering Council by the creation of the ECUK, a rather clumsy acronym for Engineering Council UK. The new body will regulate the profession and the institutions have joined together with representatives of industry and with government to produce the Engineering and Technology Board, the ETB.

Cleaning up the act

At last the institutions and industry have got together and said ‘we have to clean up our act in terms of how we present ourselves to society, to Government and particularly to the young if we are going to help to reverse these trends which will hamper us in securing skilled manpower in the years to come’. Broadly, we are trying to arrest this declining interest in science and maths at A level and, of course, the threat to university enrolment in engineering. We are here to communicate the excitement of engineering and technology to society as a whole. According to my job spec, the ETB has been set up to promote cohesion between the world of science and the world of engineering. How could I do other than preach my message of continuum, that basically there is no division between science and engineering in a debate such as this one this evening?

There is another player on the scene. I have been delighted to play a very small part at Gareth Roberts’ shoulder, as he has been putting together and piloting the Science Council to bring together the science institutions, the mathematics institutions and, indeed, a number of the engineering institutions under one umbrella so that they, in turn, can also speak with one voice. We are discussing next week the concept of whether, as an analogue to a chartered engineering status in the world of engineering, there should be chartered scientific status in the world of science, something with which I heartily agree. Given the nature of the problems we are tackling, should there simply be one entity, representing the whole of this continuum under a single banner, looking at the chartering and registration of professionals, a single gold standard that industry, society and Government would acknowledge?

In conclusion I believe that the purpose of this evening is not constructive contention between three speakers. My hope is that we will all unite in the analysis of the situation. Unless we pool our professional disciplines together, unless we project ourselves coherently to the young, we are going to be facing far worse statistics when a similar gathering assembles in 10 years' time. I am absolutely confident and optimistic that that will not be the case. The programme of the ETB, working with Gareth Roberts and the Science Council, will address these issues. I am fascinated to hear whether Alec joins in this 'love-in' that Bob and I have started by agreeing with each other and, even more, I shall be fascinated to hear what the workshop participants feel about these issues. ❐

Addressing the outcome

Sir Alec Broers FRS FREng

Sir Alec Broers is President of The Royal Academy of Engineering and Vice-Chancellor of the University of Cambridge. Sir Alec was educated in Melbourne and Cambridge in physics and electronics and worked for IBM first at the Thomas J Watson Research Centre in New York, then in the East Fishkill Development Laboratory and finally at the Corporate Headquarters, before returning to Cambridge in 1984

The question I wish to address is one of outcomes: "how should science, technology and engineering research and innovation be organised in order that the UK becomes a world leader in applying science and technology for the benefit of mankind?" I'm interested in how we can regain a position of leadership in the production of important high technology products, rather than in scientific papers as raw material for citation analysis.

To answer this question I am going to ask four questions of my own. 'Are science and engineering different?' 'Which is more important?' 'Is it worth trying to define the boundaries between them?' and 'Do they require a different education?'

Key IT development

To illustrate how successful technologies are implemented, I will describe briefly the development of some key IT technologies: magnetic recording, electronics, the transistor and the integrated circuit chip.

Magnetic recording was first demonstrated by the Danish engineer Vladimir Poulsen in 1900 using iron wire. Plastic recording tape coated with iron oxide was developed in Germany during the First World War using the vast resources of the German government. Its use for recording data for accounting purposes was investigated by James Bryce in 1937 who started a project in 1941 that led to the first computer tape memory systems in 1953.

Disk magnetic memory technology was first explored in the early 1950s at the National Bureau of Standards in Washington based on ideas of Jacob Rabinow and the first successful writing and reading from a multi-disk recorder was demonstrated by IBM in February 1954. IBM delivered the first RAMAC (Random Access Memory Accounting Machine) disk file in June 1956.

So industry and a national laboratory had worked together to come up with the first disk recorders. By modern standards these had very small capacity, 25 megabytes and were very large, occupying the size of a small room, but they were remarkable at the time. Since then dramatic progress has been made with magnetic tapes and disks through improvements in magnetic media, and by reductions in the recording head gap and the spacing between the head and the tape. A laptop computer now has a disk with several thousands times the capacity of the RAMAC file.

Magnetic recording therefore began with an individual engineer and was then developed by multidisciplinary groups supported by Government and industry. More than a 100,000 times increase in density has been achieved over the last 50 years as a result of progress in materials science, mechanical engineering and electronics – a similar mixture of disciplines to that involved in the MRI story just told by Peter Williams. This phenomenal progress is rivalled only by that of the semiconductor industry.

The story with electronics is similar. The technology for the electronic vacuum valve had its roots in the experiments of physicists studying cathode rays. J J Thomson discovered that these rays were in fact streams of particles - 'electrons'. He was using simple equipment. We can't do much today with such simple equipment, but I will return to this point later.

The valve, which was based on Thomson's simple equipment, was developed as an amplifying device to detect Marconi's electromagnetic radiation signals. The major advances were made by the electrical engineer De Forest and the Nobel Prize winning chemist Langmuir both working almost as individuals. The technology was then rapidly developed by government sponsored research during and after the First World War.

Electronics, which was based on the experimental discoveries of physicists, began with individuals but was brought to practical application in the large laboratories of Government and industry by multidisciplinary groups.

discussion

Institutions. While there was some criticism of professional institutions, some of whose attitudes were historically restrictive, and some of whose leaders were caustically described as 'past their sell by date', there was also recognition that they were actively seeking to advance multidisciplinary working and were cooperating with the development of the Engineering and Technology Board and ECUK. There were, for example, more paths opening up for the award of Chartered Engineer status and dual membership of institutions with a single qualification becoming possible. But Institutions were still, in essence, tribes or clubs and the aim of the founders of the 1851 Commission, to get science and art to work together for the requirements of industry, still had to be met. Collaboration depended essentially on the individuals who were willing to make multidisciplinary processes work, and there was still sand in the institutional structures. One speaker described his 'random walk' in science, through various disciplines, and noted that this had lead to him failing to attain membership of any professional body.

My next example is the transistor. The transistor was developed by the physicists Bardeen, Brattain and Shockley at Bell Telephone Laboratories in a research project focused on developing a solid-state version of the electronic vacuum valve. It was known that this was likely to be made from the semiconductors that had been used to make rectifiers, regulators and modulators in the intensive Second World War effort in Britain. It was not blue-sky research but research carefully focused on an area with great potential for technological development.

Following the initial experiments at Bell Labs, the practical transistor was developed by industrial research groups containing electrical engineers and physicists.

That was how it began, but the transistor did not reach its full potential until it was incorporated into the integrated circuit chip. The feasibility of the integrated circuit chip was demonstrated by the engineer, Jack Kilby working in the laboratory of a large company, Texas Instruments. Kilby demonstrated that it was possible to embed several electronic components, including transistors, into a single piece of silicon. The subsequent extraordinary progress has been the result of the efforts of vast multidisciplinary research teams containing engineers, physicists, material scientists, mathematicians, chemists and so on in the world's leading industrial laboratories.

I won't trace optical fibre development but there again is a story that starts with individuals but it is the contributions made by teams of engineers and scientists in the laboratories of large companies that brought the original elementary ideas to practicable fruition. And it is only after this that the real potential of the idea emerged.

Evolution of ideas

These are just a few of the technologies that have led to the information and communication revolutions. I have in fact analysed more than 20 such technologies and I have drawn the following conclusion:

Most technological advances have been made by solving problems at technology frontiers. Quantum leaps forward have been rare as have revolutionary concepts.

Technologies based on revolutionary concepts have taken a long time to implement and the science and innovative engineering needed in their implementation has often been as important as that needed in their invention.

Most of the significant technological advances of the last 60 years have been made by multidisciplinary research teams in large enterprises. The ideas, of course, come from individuals but unless these ideas fit into a matrix of innovation significant progress is rarely made.

Many innovations made in large companies have not been perceived to fall within the business interests of these companies and spin-offs and start-ups have captured their commercial potential. But spin-offs that do not work on the base technology themselves seldom grow beyond small or medium size.

New materials are almost always necessary for significant advancement in base technologies.

A sophisticated understanding of human physiology and psychology is essential in developing new electronic communications and entertainment products.

The pace of industrial development has accelerated to the point that many products become out of date within a few years.

Expenditures on single R&D projects in the IT, communications and transport industries exceed a billion pounds and progress cannot be made without the latest equipment and techniques.

So, overall I have concluded that to be successful in the development of modern technologies one must have large teams of engineers and scientists with a sophisticated insight into their subjects, and they must be given adequate resources. This is unlikely to be achieved in small- and medium-sized enterprises although these are important in the generation and early development of new ideas. In the UK we need to maintain thriving large enterprises, whether they are private corporations or nationally supported university laboratories, as well as to encourage small- and medium-sized enterprises.

I will turn now to the parts that engineers and scientists must play in the evolution of new technologies.

The roles and education of engineers and scientists

If they are to be effective, engineers must have an in-depth understanding of the science that underpins the technology they are working on, and scientists must have an understanding of the practicalities and economics of technology. In other words, engineers and scientists lose their identities as they work together in the development of modern technology and it is not uncommon to find mathematicians working on the practicalities of an application, and engineers spending their time on mathematical modelling. With biotechnology, the interface between the physical and the biological sciences also needs to be bridged.

Believing this, I conclude that all students need cultural breadth and should carry a mix of arts, humanities and science throughout their schooling. Students entering university should be given the opportunity, if they wish, to take a broad spectrum of subjects and that separation of science and engineering courses need not occur until the final two years of an undergraduate degree. I also think that engineers and scientists who want to develop science for the practical benefit of mankind need mathematics plus as broad a base of the physical and biological sciences as is practicable.

Finally, I will answer the questions I posed at the beginning of my talk.

Are science and engineering different? Only in emphasis and purpose. (Scientists frequently pursue curiosity-based research, whereas engineers are almost always confined to topics that have practical application.)

Which is more important? They are of equal importance.

Is it worth trying to define the boundaries between them? No.

Do they require a different education? Only in the final years of tertiary education. ❐

The science of climate change: adapt, mitigate or ignore?

The Foundation's Ninth Zuckerman Lecture was delivered on 31 October 2002 at the Royal Society by Professor Sir David King KB ScD FRS. Professor King has been Chief Scientific Adviser to the Government since 2000. The evening's event is summarised by Sir Geoffrey de Deney KCVO.

Professor King began by emphasising that the subject was one that crossed many boundaries, national and cultural, and its international importance required scientists and politicians to work together. Illustrating the reconstruction of the temperature history of the globe through the measurement of ice cores, Professor King instanced the reduction of the ice cap of Kilimanjaro from 12.1 km^2 in 1912 to 2.25 km^2 in 1998. It was estimated that the cap would have disappeared by 2015.

Factors contributing to this effect had first been identified by the French mathematician and crystallographer, Jean Baptiste Fourier in the early 19th century. He had coined the term global warming to describe the effect of heat from the sun penetrating the earth's atmosphere, the resulting warmth being retained by that atmosphere. In itself, that process is benign; in 1860 John Tyndall measured heat by reference to carbon dioxide and water vapour and developed the theory that changes in the carbon dioxide emissions determined the cycle of ice ages.

In 1896, Svante Arrhenius (Sweden) made the attempt to estimate quantitatively the effect of carbon dioxide emissions on global temperature, predicting that a doubling in the volume of such emissions would produce a rise in temperature of 5 to 6 degrees centigrade, a figure close to modern estimates. In an address to the Royal Society in 1936, Callender advised that, based on data since 1882, global warming was taking place, a view that did not then find acceptance.

From the late 1940s, Harvard Professor Roger Revell was a diligent and influential proponent of the view that carbon dioxide accumulation would cause global warming. Since 1965, when the White House first ordered a study of the phenomenon, international scientific activity has gathered pace in the UN, the United States and various intergovernmental studies.

Professor King illustrated the current state of knowledge by a series of graphs, the first showing carbon dioxide emissions over the past 60,000 years, during which the ceiling of 280 parts per million had not been breached until the last century, when it had begun to climb to the current figure of 375 p.p.m. Future predictions considered alternative estimates of rises by AD 2100 to 550 p.p.m. and 1,000 p.p.m. respectively. Predictions of increases of temperature by the end of this century were subject to wide margins of error, but ranged from 1.5 to 5.0 degrees centigrade.

The question to be answered was whether there was a causal relationship. Human activities giving rise to temperature increases comprised emissions of carbon dioxide, methane, nitric oxide and sulphur. A comparison, for the years between 1860 and 2000, between the computer simulated model and observed results showed close congruence. It was reasonable, therefore, to accept a causal link.

The longevity of carbon dioxide in the atmosphere complicated counter measures. Even if emissions were immediately halted at their present level, stabilisation could take up to 300 years and the concentration would not then reduce. The effects of temperature changes resulting from such developments have alarming consequences for sea levels, both as a result of thermal expansion of the oceans and melting ice caps. By AD 2080 Arctic sea ice is likely to have nearly disappeared and Antarctic sea ice to have reduced by 10 per cent.

A series of maps illustrated the effect of rises in global sea levels of 3m, 10m and 30m respectively on the North American coastline and on the number of people likely to be flooded in India, Southeast Asia and Africa. If no attempt to reduce carbon dioxide emissions were made, the numbers likely to be affected in this way could rise to hundreds of millions by 2080. Reductions of carbon dioxide concentrations to 750 p.p.m. or 550 p.p.m. would have progressively less devastating effects, but would still be serious, having economic, financial, social and political implications. The Association of Small Island States had estimated that if stabilisation at 550 p.p.m. could be achieved, 90 per cent of their territory might be preserved. There were, however, already increased storms and a progressive

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Nuclear power. A number of points were made in relation to nuclear power:

- Doubts were expressed about the timescale envisaged for the development of fusion;
- A certain amount of radioactive waste is produced during nuclear fusion;
- More efficient fission plants are now available and should be installed;
- The use of nuclear energy faced substantial political and environmental opposition, attributable not least to the problem of waste disposal;
- The centre of gravity for the development of fission plants was shifting from the USA to Europe and South and East Asia;
- With the development of more efficient plants the public needed to be convinced of their acceptability and reassured about waste disposal.

reduction in biodiversity - for example, there had already been a loss of coral species and a depletion of coral-reef organisms.

The options for future policy were to do nothing, leaving the solution to market forces, to mitigate, by reducing the extent of the effects, or to adapt by managing change. Mitigation and adaptation were not mutually exclusive courses.

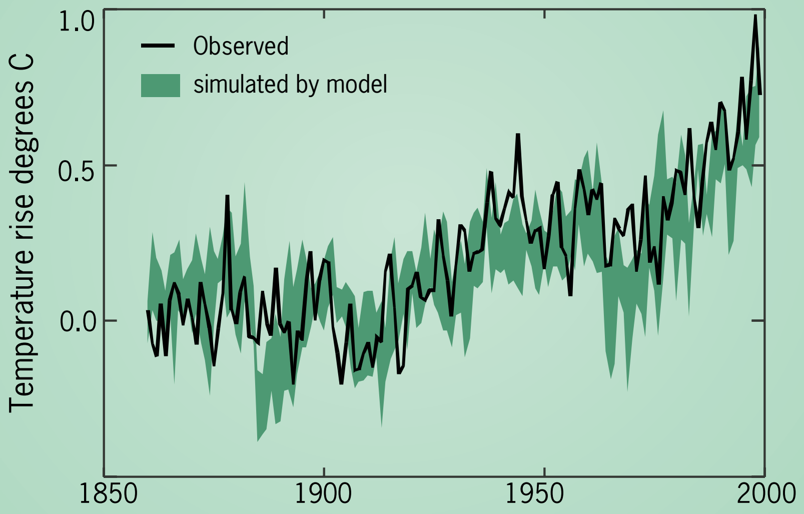
A graph of past and estimated future oil production showed that, while the slowing of production imposed by the OPEC producers in the 1970s had delayed the process, exhaustion of world supplies at present rates of consumption could be expected unless alternative sources of energy were developed. Already, by 2009 it was likely that 50 per cent of all oil supplies would be in the Middle East and unit cost of production might rise to US $1 a gallon. The total exhaustion of world oil supplies would be a step that would be irreversible and must not be allowed to happen.

Alternative fuel sources, however, were not without complications. Developments in automobile engineering seemed likely to enable cars using alternative fuel sources to be commercially available in 10 to 15 years but these might well impose additional demands on the national grid.

Economic modelling does not support resort to inaction. A 60 per cent reduction of emissions is needed by AD 2050. For this it will be essential to secure the cooperation of the United States. Consumption of oil there is 21 tonnes per head annually, compared with 9 tonnes in Britain. A critical element is the energy mix, and in this the GDP is a factor.

A range of options existed to mitigate emissions:
- Improve efficiency of energy usage;
- Invest in R&D in renewable energy, carbon sequestration and fusion;
- Engage actively in North - South Science Engineering and Technology capacity buildings;
- Avoid exceeding a particular temperature/carbon dioxide global targets threshold.

Simulated global warming 1860–2000
Natural and man-made factors



Source: Hadley Centre/Met Office

The 2001 Energy Review by the Performance and Investment Unit (PIU - now the strategy unit) had identified six key areas for increased R&D investment:
- Carbon sequestration
- Energy efficiency
- Hydrogen
- Nuclear
- Solar PV
- Wave and Tidal

Work on proposals, including finance, for the establishment of a national research centre to boost energy research in Britain was in hand in the research councils. A key element was the development of nuclear fusion as an energy source. Work on the JET project at Culham was complete. The next stage was the ITER project. A successful outcome might be 25-30 years away.

In the British energy mix, if no increase in nuclear power was achieved by 2020, the fossil fuel element in total consumption would exceed the PIU objectives by 3 per cent whereas an increase in the nuclear element to 27 per cent would bring down the fossil fuel element to 20 per cent.

In the field of possible adaptations, the most recent significant flood in London had been in 1928. Since then the Thames Barrier had been installed. A measure of the flooding that had been averted could be gauged from the frequency with which the Barrier had had to be raised. This had increased to 15 occasions in 2001. The estimated saving in the costs of flood damage far outweighed the cost of installation. Yet 10 per cent of housing stock was now located in flood plains with serious implications for insurance and finance.

It was difficult to estimate the cost of stabilising carbon dioxide emissions. The figure might exceed trillions of US dollars. But the financial implications of the alternatives were incalculable. The disappearance of the Antarctic ice cap would be likely to result in an increase of sea levels globally of 100m. ❐

discussion

Sequestration and alternatives. There was some discussion of carbon sequestration. This was at present very much in the R & D phase. Various possibilities were under consideration.

Reference was made to the problems of exploiting wind power in the UK, given the number of wind generators necessary. But no possible alternative should be ignored. Work was similarly progressing on the use of tidal power.

Other alternative approaches involved the development of adequate computer power, for example to re-route container ships so as to shorten journeys by taking advantage of the Arctic route. This was already in hand. Computer capacity was similarly needed to tackle the problem of modelling complex climate systems.

Overall, there was general recognition of the need for adequate financial investment across the board to meet the challenges.

Beyond Moore's Law

On 9 July 2002 the implications of an end to Moore's Law were debated at an FST dinner/discussion meeting, held at the Royal Society. Should Government intervene to support innovation in science, technology and engineering in the area of microprocessor development and manufacture?

Professor John Enderby CBE FRS
Physical Secretary and Vice-President,
The Royal Society

Moore's Law, named after the US chemist Gordon Moore, is simply stated: the processing power of computer chips doubles every year and a half, which is nearly a 100-fold increase every decade. Thus in the mid-1960s, the most advanced computer chips had 64 transistor-like devices on a single piece of silicon, but Intel's latest chip, the Pentium-4, embodies an incredible 40 million transistors. This increase of device density was achieved by reducing the size of individual transistors: length scales are now a hundred or so nanometres[1], and are still falling.

Can this scaling – and the associated complexity – continue? There are some very tough physics limits to contend with. First, power dissipation is limited to about 100W cm^{-2}. But the energy required to write one bit must be greater than the average energy of thermal fluctuations. Then there is the quantum limit arising from the uncertainty principle, which is a lower limit for the sizes of components.

The *International Technology Roadmap for Semiconductors* (ITRS) spells out the problems of maintaining Moore's Law, and concludes that there are "no known solutions". In other words, within the next decade, known technological capabilities will approach or have reached their limits.

Would that matter? Some would say no, because current chip-based devices are already adequate for our needs. Moreover, the costs of going beyond silicon would be astronomical; the money and human resources would be better used for other projects. Others hold that the focus on device performance is misplaced and that it is overall system performance that matters. IBM vice-president Davari believes that it should be possible "ultimately [to] increase computer performance by five times even if device performance remains the same".

But there are strongly held views that the possible end of Moore's Law does indeed matter. Some hold that it has been a major driver of the global economy: US Internet traffic has grown exponentially since 1970; from 1997 to 2000, it grew by 280 per cent a year. Consumer demand for smarter devices will persist and the pressures on device performance will follow network developments such as the GRID.

Several emerging logic devices are identified in the ITRS report, including single-electron transistors, nanotube and molecular devices. The report also identifies emerging architectures, which include 3D integration, cellular non-linear networks and quantum computing.

How is the UK involved? We have real strengths in the academic sector: 92 departments of physics, chemistry, electrical engineering, computer science and materials received grades of 5 or 5* in the recent Research Assessment Exercise (RAE). We also have major centres of excellence such as the NPL, RAL and Daresbury. Although we have no major fabrication facilities, we do have strong sectors in software, microprocessor design and implementation, customised intellectual property and expertise in networks.

My view is that we should not attempt to 'pick a winner' from the emerging technologies, but rather develop generic technologies building on our strengths. These include metrology, lithography (both top-down and, through self-assembly, bottom up), simulation (with quantum effects built in) and new materials (compounds, spintronics, soft matter…).

My conclusion is that the end of Moore's Law raises issues of policy that should be addressed even if the outcome is negative. We have both the human resources and infrastructures to make a contribution, although there may be a case for a more focused approach to exploit our strengths.

Sir Alec Broers FRS FREng
Vice-Chancellor, University of Cambridge

I shall look at the issues John Enderby raised from a technological perspective.

It is true that we have come from the modest 16-transistor chips in 1964 to the modern Pentium processor with many millions, but the 4Gb memory chip has an even greater density, with something like 4 thousand million separately designed transistors. Because they are linked in the third dimension, the limits are not only size, but complexity. Such a chip has a significantly greater degree of complexity than, say, a world map with every street individually identified.

Yet the ITRS report is, in my opinion, over-optimistic in suggesting that we can go from the present length scale of 130 nanometres to 10 nanometres. At that scale, we shall get into real trouble. X-ray lithography could get us there, but the UV techniques of today will run out before it can be perfected. When I made a structure with 10nm electrical conductors, the technique I used would take one and a quarter years to expose a single wafer; to be competitive, you have to do it in 30 seconds.

Further scale reduction is therefore a major challenge financially (UV cameras for lithography are already approaching the $100 million mark) and technically —the ITRS says that, beyond 2010, there are no known lithography solutions. IBM is looking at electron-beam projection lithography, but that has its own set of as-yet unsolved problems. Personally, I do not think it practicable to manufacture computer chips by a

discussion

Social democracy. The French capacity to succeed with very large programmes, such as their nuclear power stations, was cited as a problem for Professor Kay's thesis. It was suggested that there was nothing in France which conformed to his model of disciplined pluralism apart from the wine trade. The theory perhaps had to accommodate a French exception. Explaining this was a challenge, but part of the answer might be that France was a rare example of a well-run social democracy managed by a relatively homogeneous group of very clever people.
Interdisciplinarity. Several disciplines needed to be involved in the design of semiconductors, and a number of speakers saw problems in communication between, for example, engineers and physicists. The Americans were seen as better at that. The proposed new UK centre was seen as mainly concerned with design, and probably employing mathematicians more than physicists. There was nevertheless a key problem of the separation of science from technology in the UK, with a weakness when it came to generating marketable products. Gordon Moore was a chemist who knew how to make silicon chips using chemical etching.

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[1] One nanometre is 10^{-9} m or 0.0000000001 metres. See ref. 2 for details of current length scales.

[2] *International Technology Roadmap for Semiconductors*, Semiconductor Industry Association. www.sematech.org

discussion

Processor capacity. To one speaker, the title of the debate tended to imply that processor capacity was the constraint on the performance of the devices that used them. In fact full use was not made of the existing processors. There were many good ideas but few came to the market. Historically designers in the UK had come up with many products, some of which had survived.

Another speaker recalled being amazed when the Berlin Wall came down to learn what clever things had been done in East Germany with primitive computer power by using very clever algorithms. Physics was perhaps not the ultimate constraint on what microprocessors could be made to do.

refinement of the stamping technique used for manufacturing compact disks.

Finally, there is the need to recoup the costs of research and development. As the price per processed bit falls to zero, the necessary development cost escalates. Look at the stores on the Edgware Road: no sooner has the 850-MHz machine appeared then there is one at 1,200 MHz and so on. Each new generation costs Intel and the other manufacturers a fortune.

I conclude that scale reduction might continue for 10 or so years, but that Moore’s Law will cease to apply within 15 years. IBM’s success in getting the copper interconnect to work extended devices by a couple of generations. Other such developments may push Moore’s Law beyond where scaling will take it, but not more than a couple or so generations.

Is there a role for Britain? I believe the answer is yes, but not in the manufacture of state-of–the-art chips .We should concentrate on advanced devices and processors where, like Enderby, I believe we could make a major contribution. There must be a collaborative effort between industry, research councils and academia.

The Royal Academy of Engineering, in its submission to the House of Lords Select Committee, advocated a national centre for integrated circuit design. Its view was that it would be fatal for Britain to drop out of the integrated circuit business. The centre would generate intellectual property, would attract inward investment and would be a place where our best engineers and scientists could be trained and retrained. It would cost about £10 million in the first year, tapering off to zero in ten years. With industry and academic partnerships, the opportunities for Britain would be enhanced while spin-offs and the IP would benefit the economy as a whole.

Professor John Kay FBA
John Kay Associates

I do not understand the technology underlying this discussion but I have spent much time trying to understand how market economies operate and develop. The mainsprings, in my view, are the interactions between technology on the one hand and economic and political institutions on the other. The driver for success is what I will call ‘disciplined pluralism’ — an environment in which many experiments are tried but where the unsuccessful ones are cut off quickly. I give two examples to illustrate what I mean.

When the British electricity industry was nationalised in 1948, the supply companies (most of which were already publicly owned) were brought together and centralised. In the early 1960s, Lord Plowden (one of the first of ‘the Great and the Good’) was asked to review the industry. He concluded that it should speak with ‘one voice’ and that the divergent views within it should be melded into a single view, which could then be put to the public and ministers.

The stage was set, following a series of power cuts in 1964 and 1965, for a nuclear power programme based on five advanced gas cooled reactors (AGRs) whose basic design was taken from a small Atomic Energy Authority prototype. Subsequently the number was increased to seven AGRs. Announcing this decision, the energy minister proudly referred to the export potential and declared that we had ‘a winner’.

We did not. Eleven years later, the economist David Henderson gave a lecture on two British technological disasters, the AGR programme and Concorde. Not until the early 1980s did the AGRs put electricity into the grid. The total cost of building the AGRs was, at mid-1990s prices, £100 billion or roughly the total spending on UK universities over the same period. When it was privatised in 1996 as British Energy, the sum raised was £1.5 billion — but thrown into the deal was a pressurised water reactor (cost: £3 billion) and a commitment to deal with future liabilities. The value of the AGRs was zero or less.

Contrast this with the development of the personal computer (PC). Early on, Intel designed a general-purpose processor so that applications software could be installed in memory. Xerox developed what was called, at the time, a ‘Rolls Royce’ machine that was too expensive to have popular appeal. The first home computers were really for hobbyists – kits had to be assembled at home. People like Bill Gates dropped out of Harvard to write a simple operating program. Hobby PCs with names like Commodore and Acorn became popular.

The dog that did not bark was IBM, which in 1981 launched the first true multipurpose PC with an operating system bought from Microsoft (which itself had bought it from someone else) and with processors manufactured by Intel. Microsoft and Intel did very well because they retained the IP rights. Steve Jobs (Apple) used an earlier idea of Xerox and developed the graphical user interface but, by insisting that the hardware and the software were built together, made commercial success difficult.

In other words, there were many players, some successful, most not. The whole process was essentially a random series of experiments, but with a market discipline that ensured that failed experiments were stopped (even though many of them had contributed to the design of the PC).

The contrast between the development of the PC and its sequels and the AGR story could not be clearer. The disciplined pluralism that characterised the former was totally absent from the latter. It is not just that governments cannot see the future of new industries — nobody can. This is why a pluralistic approach, but with the firm discipline of the market, is the only sensible option.

That leads me to ask what governments should do to promote innovation in the field of microprocessors, or indeed in any other field? First, they must be primarily concerned with the framework of basic scientific knowledge. What the government should not do is to look for the next big idea and then throw resources at it. The suppression of pluralism and the adoption of a single voice have been as damaging in British education as they have been to British energy.

The key issue for governments is the balance between open systems of innovation, where incremental improvements are made after peer review (as happens in surgical procedures), and closed systems that are heavily protected by patents and proprietary rights, as in the pharmaceutical industry. The computer industry has developed by a mixture of both models. Government policy has a major influence on whether the innovative process is open or closed; it must be scrutinised carefully both in general and in relation to specific industries.

In Britain we have suffered from a lack of disciplined pluralism. The research funds provided by the Wellcome Trust have yielded benefits quite disproportionate to the amount of money involved and remind us how important plurality of funding is to the scientific enterprise. Governments find it desperately difficult to promote pluralism; their instinct is to centralise. Yet pluralism is at the heart of the innovation process. ❐

that of who else will be after that gas and what will be the effect on prices. That is another question we must try to answer.

Back then to costs. Cost is hugely important to individuals and to the economy as a whole. Markets have delivered huge economic benefits. Further liberalisation is crucial if the European energy markets are to be as open as our increasing dependence on Europe for supplies requires; we are concerned about prices in the future and we need to do more work on that.

I have given you a brief picture of the kinds of tensions we are trying to reconcile in the White Paper. There are two other considerations that are particularly important to our work.

First, the international dimension is crucial. We are now linked physically to Europe through inter-connectors and financially through European and global investment markets. We are also linked very closely politically to Europe, particularly through the EU but also through our membership of international organisations such as the International Energy Authority (IEA) and the Organisation for Economic Cooperation and Development (OECD). For example, the EU's Large Combustion Plant Directive will start to bite particularly on coal-fired plants from 2008 onwards. There are proposals in the EU pipeline for an emissions trading scheme that will probably begin on a voluntary basis in 2005 and become mandatory from 2008. We have to plan that a European trading scheme will be central to the way we manage carbon emissions in Britain.

We also need to think ahead, again in a European context, about transport. At present, we have voluntary agreements with manufacturers to reduce CO_2 vehicle emissions, but as yet there is nothing in place beyond 2008.

There is a particular further issue on which we are working. You have heard earlier of the potential use of depleted oilwells in the North Sea for storing sequestered CO_2. But disposal in the North Sea is governed by the Oslo and London (anti-dumping) conventions. Although the conventions allow the use of gas injection for improving oil recovery, there is a view that they would forbid putting CO_2 down there, plugging it and hoping it will stay there. So we are working on that.

Clearly CO_2 is a global issue. We have to remember that we produce only a little more than 2 per cent of the total CO_2; other players will have to be brought to this party if we are to have a serious impact.

The second theme I would emphasise is that there is a powerful science and innovation dimension to what we are doing. Professor David King's PIU report has identified a number of technologies we ought to be tackling urgently – CO_2 sequestration, energy efficiency, hydrogen production and storage, nuclear power, solar, wave and tidal. But if hydrogen is to be the fuel of the future, we shall need electricity to produce it. I agree with David Fisk's point that our current mindset makes us think of 'big kit' generation when we may need to change to distributed generation, smart meters and so on. There are huge implications that need thinking through.

At this point you will appreciate that this White Paper raises many complex questions and that we have very little time in which to answer them. Our goal is to produce policies that are: (1) **coherent** between the supply side and the demand side as far as that is possible; (2) **transparent**, so that people know what is going on; (3) **stable** in the sense that forward investment will not be frustrated by regulatory risks and (4) **deliverable**. ❐

events

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Pathological Specimens and Data - What controls should be in place?

Professor Nick Wright FMedSci, Warden, Barts Hospital and The London School of Medicine and Dentistry
Mr Steve Catling, Chief Executive, The Retained Organs Commission
Dr Robert Coleman, Chief Scientific Officer, Pharmagene Laboratories Ltd
Cancer Research UK, Department of Health, Medical Research Council, The Wellcome Trust

1 May 2002

Asymmetric Warfare

Sir Keith O'Nions FRS, Chief Scientific Adviser, Ministry of Defence
Mr David Veness CBE QPM, Assistant Commissioner, Specialist Operations, Metropolitan Police
Mr Mike Granatt CB, Head of Civil Contingencies Secretariat, Cabinet Office
Qinetiq, Ministry of Defence, Science Systems Limited

22 May 2002

Science, Technology and Sustainability

Professor David King FRS, Chief Scientific Adviser to the UK Government and Head, Office of Science and Technology, DTI
Professor Sir Brian Heap CBE ScD FRS, Master, St Edmund's College, Cambridge
Ms Sarah Roberts, Manager, Global Environment and Risk, Arthur D Little
EMTA, Department for Environment, Food and Rural Affairs, Department for Transport, Local Government and the Regions

25 June 2002

Science, Engineering and Technology

The Lord May of Oxford AC PRS, President, The Royal Society
Sir Peter Williams CBE FRS FREng, Chairman, The Engineering Technology Board
Sir Alec Broers FRS FREng, President, The Royal Academy of Engineering
The Royal Commission for the Exhibition of 1851

9 July 2002

Beyond Moore's Law – does the UK have the research expertise to take a lead in the next generation of microprocessors?

Professor John Enderby CBE FRS, Physical Secretary and Vice-President, The Royal Society
Sir Alec Broers FRS FREng, Vice-Chancellor, University of Cambridge
Professor John Kay, Economist and Writer
ARM, British Computer Society, The Institution of Electrical Engineers, The Institute of Physics

16 July 2002

Priorities for Research and Innovation in the UK

Dr John Taylor OBE FRS FREng, Director General of the Research Councils, Office of Science and Technology
Dr Alastair Keddie, Acting Director General Innovation, DTI
Professor Ian Halliday, Chief Executive, PPARC
Office of Science and Technology, DTI

25 July 2002

Energy Policy

Office of the Deputy Prime Minister, Department of Transport, NERC and Science Systems Limited
Mr Tony Meggs, Group Vice President Technology, BP
Mr Rob Wright, Director Energy Policy, DTI
Professor David Fisk FREng, Imperial College

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