Foresight review of how science and technology could contribute to better energy management in the future

Executive Summary and Overview Report

This report was commissioned by the Foresight Programme of the Office of Science and Innovation to support this review. The views are not the official point of view of any organisation or individual, are independent of Government and do not constitute government policy.

Executive summary

This review aimed to provide an overview of the present state of technical knowledge and of the issues and longer-term future opportunities in respect of energy use and supply in the UK. The scope was longer-term horizon scanning rather than detailed investigation of short-term questions.

The project drew on three strands of evidence and informed opinion:

- discussions with senior business people and professionals
- a review of 'energy futures' studies conducted by other agencies
- a commissioned set of state-of-science papers, discussed at a workshop attended by academic and professional experts.

Details are documented separately and, along with the peer-reviewed science papers, are published on the Foresight website. The overview report draws out the main findings from the three strands of work. Key messages are:

- We have to find a way to reduce energy use in the short and medium term as it will take decades before we realise the full potential of the technical opportunities that are expected to address CO_2 emissions and security of supply, and to provide unlimited clean energy sources.
- We are looking at socio-technical systems, so policy makers should not focus on technological options in isolation from the social sciences.
- There are technologies that offer a range of opportunities to deliver short- to medium-term efficiencies (2–20 years) but their success is not guaranteed. The challenges are to create willingness for widespread adoption of solutions (e.g. insulation and low-energy lighting), and willingness to change behaviours to deliver sustainable patterns of life.
- In the longer term (35–40+ years), there are potential technologies that might help to manage limited energy resources (e.g. new storage solutions), and potential technologies that might unlock unlimited energy resources without greenhouse gas emissions (e.g. new photovoltaic technologies, or nuclear fusion).
- The realisation of a number of potential technological opportunities depends upon key breakthroughs in the material sciences, for example the development of materials that can withstand extremes of temperature. We should prioritise investment in these underpinning sciences.
- We need to find a way to build externalities into our assessment of efficiency and effectiveness in order to enable people to adopt patterns of life that reflect real costs.

- The complexity of the challenge requires an integrated, multidisciplinary, and long-term approach.

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Overview report

Introduction

This six-month review aimed to provide an overview of the present state of technical knowledge and of the future issues and longer-term opportunities in respect of energy use and supply in the UK. Its purpose was to inform interested agencies and individuals working in the area, and to provide a platform for any further exploration of energy-related futures by Foresight. In common with all Foresight activity, the scope was longer-term horizon scanning to inform challenging visions of the future, rather than detailed investigation of short-term questions.

The project drew on three strands of evidence and informed opinion:

- structured one-to-one discussions with senior business people and professionals with an interest in the energy environment

- a review of work done by other agencies looking at futures in relation to energy

- a workshop with leading academic and professional experts, building on commissioned state-of-science papers that reviewed current and anticipated scientific and technological developments. The workshop explored the associated issues and the potential for synergies and multidisciplinary approaches.

This overview sets out the key findings that emerge from across all three strands of work. The review of futures and the workshop are documented in detail and summarised separately. The state-of-science papers have been peer reviewed and are published on the Foresight website.

Key findings

Reasons for concern

The arguments as to why energy management and supply warrant serious consideration have been well rehearsed in public and expert domains for some time, and the Government published its Energy Review report, *The Energy Challenge*, in July 2006. Not surprisingly, this project confirmed the core issues as being:

- climate change and how to reduce CO_2 emissions from fossil fuels
- how to assure security of energy supply in an interconnected and uncertain world
- uncertainty about the long-term availability of conventional fossil fuels

- the strong connection between increased energy demand and economic growth
- the question of fuel poverty and energy inequalities nationally and globally.

The details of scenarios developed and the future opportunities identified by organisations vary, depending on which of these concerns is the main driver for their study. Nonetheless, the futures studies examined by the project, and the experts we talked to, agree on:

- the importance of population and demographic trends in driving patterns of energy demand
- the impact of economic growth in China, India and other rapidly developing nations
- the significance of future decisions in relation to the price of carbon and emissions
- the key role of economic and public policy steers in encouraging or inhibiting research and development and the deployment of particular technologies.

All three strands of this review's work highlighted the criticality of human attitudes and values, and individuals' behaviour, in shaping future energy demand. For example, despite significant increases in the efficiency of many aspects of the domestic electricity environment, overall consumption has increased 50% since 1990. As the number of households has grown, more and different appliances are being used, and ambient room temperatures have increased.

Behaviour change

The futures studies we examined acknowledged the need for changed behaviours, and the professionals and business leaders we talked to emphasised the centrality of this if the CO_2 emissions associated with energy demand are to be addressed. Technology experts pointed out that there are existing, mature, technologies that can make a big impact on energy consumption that are simply not being taken up (e.g. over half of homes with cavity walls don't have cavity wall insulation). This highlights the importance of the social sciences in helping us understand the factors that shape attitudes and either promote or inhibit changes in behaviour.

Social science experts are critical of an 'information deficit' model, pointing out that multiple factors are in play, consciously and unconsciously, when individuals act. The assumption that people are, firstly, ignorant of 'the facts' and, secondly, will behave differently if they are given them is not supported by the evidence on either count. Being well informed may be a necessary condition for change, but it is far from sufficient. Real-time feedback information can contribute to behaviour change – experiments are underway using new meter technology to inform households how much energy is consumed and when (for example, exposing the energy used by standby devices when nothing is perceived to be 'switched on') – but the web of social, cultural, and economic pressures and personal values that frame our actions and habits is highly complex. Moreover, factors that motivate a beneficial change in behaviour in relation to energy may turn out to be tangential to the energy issue itself. For example, double glazinggrew in popularity in part because of its soundproofing qualities.

An added problem is that messages from the media, industry, and government are mixed. We are told energy is precious – but there is social pressure and government action to maintain competitive markets to keep supply costs and customer price rises to a minimum. Air travel contributes significantly to greenhouse gas emissions – but businesses offer cheap flights ('Fly to Hong Kong for £75' was a front-page headline on the day of the review workshop). As a result, people may be confused or ambivalent.
In such an environment, even when a clear message is promoted, psychological research indicates that strong messages presented to ambivalent individuals can provoke a reaction opposite to that intended.

Tensions and conflicting priorities

The mixed messages stem in part from the complex economic and political environment in which energy is produced and consumed. The UK operates within the economic and regulatory frameworks of the EU as well as in the wider global market. The scope for unilateral action is constrained both by formal agreements and the economic and political realities of international competitiveness and globalised markets. Decisions on emissions trading, the pricing of carbon, or fiscal penalties for high energy use, taken at a national level, could be economically damaging and/or ineffective if they resulted in simply shifting business overseas. So, for example, tackling emissions from the aviation industry requires an international approach. The future success or failure of international agreements will set parameters for national choices.

Balancing the desire to price energy in a way that encourages economies of use against the desire to protect the poor from fuel poverty is a political challenge. The history of the energy market since privatisation is one where immediate economic efficiency and keeping prices as low as possible for the consumer have been the driving forces. This has had an impact on approaches to research and development and provoked debates on the extent to which energy research and development is a public good rather than a marketable commodity and, as such, might justify publicly funded and co-ordinated investment.

The regulator's remit to protect consumers' short-term interests has tended to constrain long-term investment strategies on the supply side. Infrastructure related to energy supply has long a lifespan. The UK's energy infrastructure evolved in a set of conditions very different from where we now are. The opportunities that may be open to us in the longer-term future will reflect investment decisions made today. There are arguments for 'future proofing' the system when the need for upgrade arises (i.e. building in the flexibility to accommodate possible/anticipated future technologies) and counter-arguments against spending more than is necessary now in the face of future uncertainty. The regulator is currently developing approaches to stimulate engineering innovation and incentivise greater risk taking by energy companies (the Innovation Funding Incentive and Registered Power Zones) but there are challenges to demonstrating that innovations in distribution technology are robust when deployed and commercially viable.

A further challenge is creating market conditions in which commercial producers and suppliers of energy are motivated to encourage their customers to consume less.

Scientific and technological opportunities

The state-of-science papers produced for us by the experts presented a range of short- to medium-term (2–15/20 years) possibilities for improving energy efficiency and/or managing energy demand. They also considered anticipated developments that could open up more radical options in the longer term (20 years and beyond). Two key uncertainties in the medium term, the outcomes of which could drive developments in differing directions, are whether carbon capture and storage is commercially realised – potentially prolonging the use of UK fossil-fuel reserves and mitigating the emissions from exploitation of fossil fuels in developing economies – and whether the theoretical potential of the hydrogen economy is technically realisable and makes economic sense (discussed further in Transport, below).

Many short- to medium-term possibilities for improving energy efficiencies and for reducing emissions rely on changes in attitudes or behaviours to provoke wider take-up of energy-saving opportunities, or need clear political and market signals to stimulate investment and deployment of emerging, and sometimes relatively expensive, technologies. Such possibilities do not depend on further, major, technical or scientific breakthroughs. In most cases, they are already happening on a small scale or in specific circumstances. Examples include: the use of variable speed motors to improve efficiency in electrical machines and appliances; growing crops for biofuels to replace fossil fuels in heat and power generation and for transport; using light-emitting diode (LED) lighting; and local combined heat and power (CHP) networks.

In the built and domestic environments, there are many technological avenues of exploration that could help improve energy efficiency, either via the design of new buildings and communities, or via computational intelligence built into appliances. However, the challenges of improving energy efficiency in existing buildings and conurbations with out-of-date infrastructure are more significant. It is anticipated that two-thirds of the buildings we will be using in 2050 already exist today. Nonetheless, there are a number of 'here and now' options (e.g. insulation, low-energy lighting, dropping the thermostat setting by a degree or so) that could make an appreciable impact.

A specific short-term goal is an increase in the proportion of our energy produced from renewable sources. There are technical and economic factors to be addressed in moving to a greater mix of energy-generation technologies and more widespread small-scale generation. An active electricity distribution network that integrates (rather than simply connects) distributed generation sources and copes with transient dynamic voltages depends on a variety of technological developments to enable the capture, processing and communication of data about the state of the system and to provide the flexibility to respond. Novel algorithms and models, intelligent software agents, advances in sensor technology, and new materials are all pre-requisites.

Longer-term possibilities for reducing emissions and improving efficiencies are generally predicated on significant technological and scientific breakthroughs to allow the theoretical or small-scale possibilities to be turned into large-scale, deployable, solutions. Examples of these more futuristic possibilities include cheap, and more efficient, photovoltaic cells; Generation IV nuclear reactors; nuclear fission; high-temperature superconductor power transmission; and technologies for storing and transporting hydrogen. Carbon capture and storage (CCS) technologies were seen by experts as a potential transitional technology. If technical and regulatory obstacles to wide-scale deployment are overcome, CCS could extend the scope of fossil-fuel stocks to provide energy while breakthroughs in renewable spheres are being realised.

Major breakthroughs in the technologies for energy storage would help unlock the potential of intermittent renewable energy sources such as wind and sun. A step-change in battery and supercapacitor storage technology will require new materials for electrodes and electrolytes, and superconducting magnetic energy storage will depend on further development of high-temperature superconductors. The potential importance of storage technology goes beyond its value in releasing the potential of the UK's renewables. Two billion people worldwide have no access to networked electricity, so the social and commercial scope for exploiting storage breakthroughs is considerable.

In a number of fields, new approaches to systems modelling and software design are seen as critical – e.g. modelling wind generating systems in a variety of weather conditions; developing software agents and information and communications technologies to help introduce greater degrees of intelligence into the management of energy demand. There are particular challenges in modelling the impact of exported microgenerated power on the distribution system.

There was greater optimism among the experts about opportunities to tackle energy demand and associated CO_2 emissions in the industrial and domestic built environments than in relation to transport. The seemingly inexorable rise in demand for travel – whether by private car or international flight – as gross national product rises around the world poses major challenges, despite the technological advances in vehicle and fuel efficiency.

Transport

Globally, transport accounts for some 57% of the world's energy use. In the UK, transport consumes around 30% of the energy we use and generates around 25% of our carbon emissions. One problem is that the transport sector has not been particularly sensitive to energy prices. In the case of cars, for example, almost all the cost is in initial capital outlay, maintenance, insurance, parking, etc., with incrementally relatively little additional cost per kilometre travelled. A recent EU-funded study that modelled the land-use/transport systems of seven major European cities, showed that the only 'policies' that reversed current trends in car use, were very large rises (by 100% and more) in the real price of motoring.

Foresight's Intelligent Infrastructure project (January 2006) indicates that the seemingly inexorable growth in travel and associated emissions could be tackled with a combination of intelligent designs, intelligent infrastructure, data to provide intelligence about the transport system, and intelligent use. To deliver such change would require significant co-ordinated action. It is, however, possible to reduce the impact of transport by: using low-carbon fuels and improving the efficiency of internal combustion engines by developing improved combustion techniques; developing new fuels; and considering other energy-saving options such as hybridisation, 'switch off when idle', and converting the heat from exhaust waste to electrical power.

The UK is already committed to replacing 5% of the fuel supplied for transport with liquid biofuels (ethanol from sugar beet/wheat, and biodiesel from oilseed rape) by 2010. With current practices and biofuel technologies, growing the crops to produce these biofuels in the UK will require around 1 million hectares of agricultural land devoted to it. It is argued that this could be found from within existing agricultural land (using 'set aside' and switching production, for example). However, it also pointed out that a further 1 million hectares is needed to meet aspirations for growing biofuels for heat and electrical power generation.

Looking further ahead, annual biofuel crops are relatively inefficient compared to perennial crops such as willow and poplar, so there is scope to change crop systems and to explore, in the longer term, so called second-generation biofuels. The UK has considerable expertise in food crop science and plant sciences but hasn't yet transferred and exploited that expertise fully in relation to fuel crops. The overall impacts of fuel crops on biodiversity and the environment, as well as their overall CO_2 efficiency when measured against the crops or vegetation they replace are not yet well understood.

There is considerable international interest in the technologies that underpin the so-called 'hydrogen economy' to tackle greenhouse gas emissions. The vision is for hydrogen to be used as an energy vector, allowing, among other things, vehicles to be powered by hydrogen fuel cells. The creation of hydrogen requires energy input, so, to deliver the reduction in emissions, this must come either from renewable sources or from fossil fuels with carbon capture technologies in place. The creation of sufficient quantities of hydrogen using clean power is one of the challenges, as production of hydrogen at present is a relatively inefficient process. Fuel cell technology exists and is in use in demonstration public transport and local heat and power schemes in the UK. However, there are major technical challenges to overcome in relation to the storage and transportation of hydrogen before widespread use as a private-vehicle fuel would be feasible.

High-speed trains would provide an energy-efficient alternative to short-haul flights, but would require major investment in upgrading the infrastructure. Increasing train capacity by use of double-decker rolling stock would require infrastructural investment, for example, replacing existing bridges over the rail network. Moreover, investment in infrastructure carries energy costs and the recovery periods are not yet well understood.

Conclusions

The evidence gathered during this short review points to a number of conclusions and areas for further work.

A central issue is the integration of the social sciences into work looking at the technological dimensions of energy production and use. Technological options will be taken up, ignored, or obstructed by human beings – acting as individual consumers, industrial and commercial players and investors, and political decision makers and policy designers. Understanding how these players interact with the technological environment and the criteria that shape their behaviours must lie at the heart of developing effective long-term strategies.

The importance of the human dimension is exposed by one of the conundrums in the energy world. Technology has delivered considerable advances in energy efficiency, as has privatisation of the electricity and gas markets, yet the net result is an overall increase in energy use. We have found new ways to use energy (computers, mobile phones, patio heating, air conditioning …) and we have replaced our inefficient appliances with new ones that are more efficient but also bigger and with greater functionality, so they actually use more energy overall than the old ones. New cars have more efficient engines, but they may well be bigger, heavier and equipped with energy-consuming devices.

The human desire to travel for leisure and willingness to travel to match work and domestic constraints combine to ensure that we travel further, as we have more disposable income for long-haul holidays and access to transport systems that allow us to commute further to work and shop. Average time spent travelling has not changed in over 30 years – around an hour a day – but this is now more likely to be 50 miles by rail or road than a few miles on foot or bicycle. More generally, economic growth is associated with increased overall energy demand, although a shift in the industrial base from manufacturing to services has tended to 'outsource' the UK's energy demand to other countries. Unless and until the potentially unlimited supplies of energy promised by nuclear fusion become a reality, a key question is how behaviour associated with economic growth can be sustained while restraining growth in energy demand and greenhouse gas emissions.

Just as critical as the social sciences are the materials sciences. Projected technological breakthroughs on which many hopes are pinned (e.g. electricity storage, responsive distribution networks, solar power, hydrogen-fuelled transportation, nuclear fusion) are contingent on the development of materials with new properties and which can withstand extreme environments. Step-changes in known technologies, notably photovoltaic cells, which will render them economically viable, are also dependent on new materials being developed that permit a radical redesign of the technology.

The work that has been done by interested organisations and experts looking at energy-related futures tends to reflect a focus on some particular perspective (e.g. electricity supply; carbon emissions; transport; new sources of energy). This limits the extent to which the studies address cross-cutting aspects and identify potential synergies or tensions, and it tends to leave gaps, for example, between issues of energy resources/generation and issues of demand. The transmission and distribution link between supply and demand is crucial and may render certain options more or less practicable. For instance, there are electricity transmission issues arising from the abundance of renewable resources (wind, wave) in remote locations far from end users, biomass needs transporting from its place of production to refineries and end users, and the fuel distribution system for motor vehicles would need to be completely redesigned if hydrogen became the fuel of choice. There are technological opportunities on the horizon to enhance the active demand-side management for electricity but they, in turn, raise questions about the flexibility and design of the distribution networks.

Much of the work undertaken on energy focuses either on one source (notably electricity, gas/fossil fuels, or renewables), or on energy uses in a specific sector such as transport. Sometimes discussions conflate 'energy' and 'electricity'. In either case, the issue of heat energy and its interrelationship with other forms of energy is under-explored. Photovoltaic electricity receives greater attention than solar thermal energy, for example. Heat accounts for over 50% of energy use in the built environment – whether for space heating or water heating – but is usually generated *in situ* using gas or electricity. Certain heat-intensive industries are able to exploit otherwise wasted heat, especially when located near to electricity generation plant. But in the domestic context, beyond a few local CHP schemes, there is no market in heat and considerable amounts of heat energy are simply dissipated by large electricity generators. There are obvious difficulties in managing the highly uneven demand for heat in the domestic environment, but this may be a topic that warrants more detailed consideration.

In assessing options that science and technology may open up in the future, a key question is how to appraise them. Lifetime financial costs that include build and decommissioning, rather than operating, costs, are considered for generation options. But the energy input, and associated carbon emissions, in manufacturing and building in general (whether the manufacture and build of power plants or the manufacture and build of new housing) are not commonly costed. For example, thermal mass in a building may help create passive (i.e.

energy-free) heating/cooling systems and can be assessed as contributing to energy savings. But others have questioned the energy input to create the necessary thermal mass in the first place and how that relates to the lifetime savings of the building's operation. Similarly, at the level of an individual vehicle, hydrogen may have energy and emissions benefits, but once creation and distribution of the hydrogen are factored in, the picture may look different. Society's willingness to factor in the externalities of environmental impact is a crucial parameter.

A related question, in a global context, is whether and how to cost in the energy implications of parts of the production process that occur overseas, such as oil and uranium extraction.

Finally, whatever the technological opportunities turn out to be in the future, they will draw on professional knowledge and expertise in devising them and will be dependent on human skills to implement, sustain and develop them. Many of the contributors to this review have expressed concerns about the future pool of intellectual and practical skills that will be available to the UK to meet future energy challenges. The issues include: limited availability of expertise in the construction and building services industries to use, install and maintain emerging technologies; over-reliance on technician-level staff, who can work with existing templates and systems but whose training limits their capacity to anticipate or respond to fundamental shifts in underpinning technology; shortage of professional engineering expertise to tackle the intellectual challenges of a more dynamic electricity grid; potential shortages of materials scientists.

The overriding conclusion is that the complexity of the challenge requires an integrated, multidisciplinary, and long-term approach.