ENERGY, ENVIRONMENT AND SUSTAINABLE DEVELOPMENT: A UK Perspective

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Energy sources of various kinds heat and power human development, but also put at risk the quality and longer-term viability of the biosphere as a result of unwanted, ‘second order’ effects. These side effects give rise to potential environmental hazards on a local, regional and global scale. Consequently balancing economic and social development with environmental protection is at the heart of the notion of sustainable development as set out in the London Communiqué; the 1997 declaration by 18 chemical engineering societies from around the world aimed at harnessing their skills to improve the quality of life. In this context, the principles and practice of sustainability are examined as they apply to the energy sector. Conflicts between the moves towards energy market liberalization and the needs of sustainable development are outlined in the light of recent experience in the United Kingdom. The likely options for a sustainable energy strategy are described, as well as some of the challenges that such approaches would pose for the engineering profession.

Keywords: primary energy resources; electricity generation; end-use energy consumption; energy systems analysis; climate change; environmental pollution; sustainable development.

INTRODUCTION

Energy sources of various kinds heat and power human development, but they also put at risk the quality and longer-term viability of the biosphere as a result of unwanted or ‘second order’ effects. Many of these side effects of energy production and consumption give rise to resource uncertainties and potential environmental hazards on a local, regional and global scale. Examples include the depletion of North Sea oil and natural gas resources, the generation of smog from urban road transport, the formation of acid rain via pollutant emissions from (primarily) fossil fuel power stations, the complexity of long-term safe storage of radioactive wastes from nuclear power plants, and the possibility of the enhanced greenhouse effects from combustion-generated pollutants. For a proper understanding of such issues Hammond has argued that it is necessary to employ a range of analytical techniques that have been developed under the umbrella of several different scientific, engineering and social science disciplines. To do otherwise than adopt an interdisciplinary, systems approach is to run the risk of missing some important element in the broad environmental canvas. Thus, national governments and regional bodies in the West (such as the European Union and the International Energy Agency) need to balance the long-term advantages and disadvantages of the available energy sources in order to reconcile the pressures induced by the move towards competitive markets with the requirements of a sustainable energy strategy. The elements of such a strategy will change over time, and the ‘optimal’ mix at any given instant will be uncertain when viewed from the present. Although it would be desirable on natural resource and environmental grounds to phase out the use of fossil fuels, this may not be feasible by the middle of the next century.

Over a period of some 15–20 years, the international community has been grappling with the task of defining the concept of ‘sustainable development’. It came to particular prominence as a result of the so-called Brundtland Report published in 1987 under the title Our Common Future; the outcome of four years of study and debate by the World Commission on Environment and Development (WCED) led by the former Prime Minister of Norway, Gro Harlem Brundtland. This Commission argued that the time had come to couple economy and ecology, so that the wider community would take responsibility for both the causes and consequences of environmental damage. Engineers have generally been slow to meet the challenge of making a reality of the notion of sustainability. Nevertheless, chemical engineers were amongst the vanguard of the engineering profession in seeing the importance of using their skills to improve the quality of life. The aspirations of the worldwide chemical engineering community to contribute to the achievement of sustainable development were encapsulated in 1997 in The London Communiqué. This was signed by the representatives of 18 chemical engineering societies from across the world when they came together to celebrate the 75th anniversary of the UK Institution of Chemical Engineers.

The present contribution seeks to examine the principles and practice of sustainability in the context of the energy sector. In the UK the energy system is almost wholly
dependent on finite fossil and nuclear fuels, with renewable energy sources accounting for 1.2% of total primary energy requirements in 1998. Sustainable development in a strict sense requires a reversal of these roles, but it is unlikely that renewable energy technologies could meet a high proportion of Britain’s energy demand before at least the middle of the 21st Century. This is partly due to the conflict between the needs of environmental sustainability and the downward economic pressures on energy prices arising from moves towards energy market liberalization. Even in the European Union, which has had a long-term policy of encouraging ‘renewables’, the target of 12% renewables use by the year 2010 is seen by many analysts as being too ambitious. Although renewables are growth technologies across much of Europe, they do not appear capable of playing a dominant role in achieving the greenhouse gas mitigation targets agreed under the Kyoto Protocol. It is therefore necessary to improve energy and end-use efficiency over the medium-term in order to extend the life of finite reserves. The various components of a sustainable energy strategy will consequently be described, as well as the challenges that such technologies pose for the engineering profession. These complement the four energy scenarios for the UK in 2050 recently postulated by the Royal Commission on Environmental Pollution (RCEP) in their parallel study of ‘energy and the environment’. The focus of the present contribution is on medium-term energy options for the period up to about 2015–2025.

ENERGY USE AND HUMAN DEVELOPMENT

Energy, Technology and Society

The evolution of modern human society has been inextricably linked to the discovery of various sources of energy and power. This historical relationship can be traced in the works of, for example, Andrews, Bronowski and Buchanan. Early societies have become identified by their state of technological development, which are known by terms such as the ‘iron age’, the ‘steam age’, and more recently the ‘nuclear age’. It is perhaps ironic in the context of the contemporary debate over alternative energy strategies that in the pre-industrial period humans relied on what are now called ‘renewable’ energy sources; those principally derived from solar energy. Thus, wind drove sail ships and windmills from medieval times, to be followed by the widespread use of water wheels. Wind is induced, in part, by the diurnal solar heating of land and sea. Likewise, solar heating of the sea leads to evaporation of water vapour, which subsequently precipitates over high land resulting in the flow of water in rivers, or its storage in lakes. Such resources became reservoirs for what are now known as large-scale and small-scale hydropower schemes. The early use of these renewables powered an essentially ‘low-energy society’, with the power output being employed in the immediate vicinity of the resource (that is to say, they have a high ‘energy gradient’).

The development of advanced, industrialized societies in the West was underpinned by the discovery of fossil fuel resources and the construction of the associated energy system infrastructure. Fire, the earliest energy source used for heating and cooking, utilized fuel wood. But the fossil fuel resource that drove the first or British ‘industrial revolution’ of the 1700s was coal. Britain was at the heart of this revolution, and was endowed with abundant coal reserves, with a nascent ‘free’ market system of commerce, and by a number of technological innovators. The latter ‘agents of change’, people like Thomas Newcomen, James Watt, and Charles Parsons, laid the foundations for both the engineering profession and the power industry in the UK. They developed ‘high-energy converters’, such as steam engines and turbines and subsequently various internal combustion engines. Hughes has argued that, particularly in countries like the newly united Germany and the USA, electric power underpinned a second industrial revolution commencing in the 1870s. A high-voltage transmission grid supplied electricity from large central stations to light and power urban centres such as Berlin and Chicago before 1914. Although coal was the energy source for ‘steam trains’, it is oil that has fuelled the motor car and which underlies the modern transport sector in industrial societies. Other sources, including natural gas, hydropower and nuclear energy, now also play an important role in powering post-Second World War (WWII) energy systems.

Economic Growth and Energy Use

Economic development at the level of the nation state is traditionally measured by economists using the concept of Gross Domestic Product (GDP). Industrial output is well represented in GDP as defined in the UK. However, domestic activities which have a large effect on energy demand, are not regarded as wealth creating and do not feature in GDP. Economic growth in the UK since 1965 is illustrated in Figure 1, along with recent official projections to 2015. This historic trend displays the classic ‘economic cycle’ about a 30 year linear progression, which has resulted in a near doubling in real GDP (at constant 1990 prices). Here it can be seen that the two oil price ‘hikes’ of 1973/74 and 1979/80 both induced an economic downturn. Consequently, the energy sector can influence GDP growth as well as vice versa.

Each set of economic forecasts depicted in Figure 1 were used by energy analysts in the Department of Trade and Industry (DTI) to generate long-run energy projections, published in 1995 and 2000 respectively. The earlier GDP forecasts, reported in Energy Paper 65 (widely identified as EP65), were based on a range of annual growth rate assumptions varying from ‘low’ (1.75%) through to ‘high’ (2.85%). They became viewed as the baseline projections during the latter part of the 1990s. However, when the British Government developed its Climate Change Programme in 1998–2000, it commissioned revised energy projections (denoted here as DTI (2000)). They utilized a new range of economic forecasts, which employ a corrected base GDP and are generally higher than those used in EP65 over the period to 2015 (see Figure 1). Differences in the projections simply serve to illustrate that long-term economic forecasting is something of a ‘black art’.

If the GDP of a particular country can be reliably projected into the future, then the corresponding energy demand can be estimated using (on either an aggregated or disaggregated basis) a simple relation of the type...
illustrated here for the UK:

\[
\text{Energy consumption (PJ)} = \text{population (millions)} \times \text{GDP per capital (£)} \times \text{energy intensity (PJ/£)} (1)
\]

(where 1 petajoule (PJ) = 10^{15} J). This expression is analogous to the so-called ‘IPAT’ equation devised by Holdren and Ehrlich\(^{15}\) for analysing environmental disruption:

\[
\text{(Environmental) impact} = \text{population} \times \text{affluence} \times \text{technology} (2)
\]

It has more recently been termed the ‘sustainability equation’ by Jacobs\(^{16}\). Affluence, or economic consumption per person, is normally measured by GDP per capita as in equation (1). In the period since the early 1960s this has tended to increase over time in the wealthy countries of the Western industrialized world, whilst typically falling in the poorer nations of the ‘Third World’. The situation with demographic growth has been quite different with, for example, almost stable populations in many affluent countries of Northern Europe. In contrast, rapid population growth has been observed in many parts of the developing world; Africa, continental Asia, and Central and South America. The stability in Northern European population size has been illustrated graphically by Hammond and Mackay\(^{13}\) for the case of the UK. They indicate only a 1/4% growth per annum over the period 1965–1995. The ‘technology’ component in the IPAT equation (2) represents the environmental damage per unit of consumption. It is analogous to the energy intensity term in equation (1). In order to determine pollutant emissions, equations (1) and (2) can be coupled to yield the so-called Kaya identity\(^{17}\)

\[
\text{CO}_2 \text{ emissions (MtC)} = \frac{\text{CO}_2}{\text{energy ratio (MtC/PJ)}} \times \text{energy consumption (PJ)} (3)
\]

Thus, the sustainability equation, and its energy or pollutant emission equivalent, suggest a multiplier effect between population, economic welfare, and emissions or resource intensity. The energy components of equation (1) are illustrated using UK primary energy consumption data for the period after 1965 in Figure 2. The energy intensity is seen to fall by around 36%, whilst the corresponding GDP per capita (see Figure 1) rose by some 80%. Consequently the energy demand for a nearly stable population size grew by about 20% over this period. Most of this growth took place prior to 1973, when energy consumption was largely unconstrained.

**Alternative Measures of Economic Welfare**

The use of the GDP as the main measure of economic welfare, or headline indicator of progress, has received criticism both in Europe and North America over recent years\(^{16,18,19}\). It is argued that this parameter is only a measure of total economic activity, and does not reflect genuine human well-being. No account is taken in the formulation of GDP of income distribution (varying inequality), or of the environmental impacts of industrial development. Crime, divorce and other elements of social breakdown appear to enhance GDP; they are therefore portrayed as economic gains\(^{18}\). For these reasons alternative measures of sustainable economic welfare have been sought by several authors\(^{18,19}\). In the USA a ‘Genuine
Progress Indicator’ (GPI) has been proposed by Cobb et al.,18 whilst in Europe an ‘Index of Sustainable Economic Welfare’ (ISEW) has been developed for several countries along similar lines. The latter work has been encouraged by the Stockholm Environment Institute, with the UK version of the ISEW being devised at the Centre for Environmental Strategy at Surrey University (see Jackson et al.19) with the support of Friends of the Earth (FoE) and the New Economics Foundation.

Both the GPI and ISEW allow for over 20 elements important to human well-being that are ignored in the conventional definition of GDP.16,18 These include ‘defensive expenditures’ (spending to offset past costs), social costs (including changes in income distribution and the real value of unpaid housework), and the depreciation of ‘natural capital’ (environmental assets and natural resources). Thus, they may act as more comprehensive indices of sustainable development. These new measures suggest that the quality of life generally rose in parallel with GDP until around 1970, and declined thereafter. The trend for the UK is illustrated in Figure 1. It implies a widening gap between notional economic activity, as measured by GDP, and genuine human welfare. This also indicates that the costs of economic expansion now exceed the benefits; the ISEW dips, whilst GDP rises geometrically. Consequently it may be argued that the continued use of GDP as the sole economic indicator will give a misleading picture of human development.

Governments have been reluctant to adopt variants of the ISEW. In the UK successive governments have highlighted the practical difficulty in valuing environmental pollution in common, monetary terms. In fact any aggregate measure of economic welfare or of environmental quality is open to criticism on the grounds of ‘resource reductionism’, implying judgements about the relative weighting of the various consumption categories, and their environmental impact.20 Such criticisms can also be levelled at concepts like the ‘environmental footprint’,16 used by Doughty and Hammond20 to assess the sustainability of cities, or the analogous ‘environmental space’ employed by FoE21 to set targets for a sustainable future in Britain. However, in many cases, they add new insights into environmental issues not provided by conventional measures. But preference has been given by UK governments22 to the development of a range of ‘sustainability indicators’ for different sectors of the economy, including the energy sector. These will be described in more detail below, but suffice to say here that they go some way to offset the under-representation of various energy intensive activities in the traditional definition of GDP.

**THE UK ENERGY SYSTEM**

**A Sectoral Framework**

Energy systems pervade industrial societies and weave a complex web of interactions that affect the daily lives of their citizens. In order to analyse rigorously the energy and environmental consequences of changes in supply and demand of energy-intensive goods and services, it is necessary to take a holistic approach. This implies drawing the system boundary quite widely; the nation state for policy decisions within the competence of national governments (for example, those influencing urban transport and air quality), regional intergovernmental blocks like the European Union where co-operation is needed to tackle problems on a continental scale (such as acid rain...
deposition), and globally for problems of the potential magnitude of the enhanced greenhouse effect. It is also important to trace the whole life of products, their associated energy flows and pollutant emissions as they pass through the economy.

A simplified model of energy flows in the United Kingdom is illustrated in Figure 3. This conceptual framework has previously been utilized by Hammond\textsuperscript{1,14}, and is similar to that devised in the late 1970s by Chesshire and Surrey\textsuperscript{23}. It should be noted that heat is wasted and energy is ‘lost’ at each stage of energy conversion and distribution, particularly in the process of electricity generation. The schematic energy flow diagram shown in Figure 3 hides many feedback loops in which primary energy sources (including fossil fuels, uranium ore and hydro-electric sites) and secondary derivatives (such as combustion and nuclear-generated electricity) themselves provide upstream energy inputs into the ‘energy transformation system’. The latter is part of the economy where a raw energy resource is converted to useful energy which can meet downstream ‘final’ or ‘end-use’ demand (Slessor\textsuperscript{24}). ‘Renewable’ energy sources are taken to mean those that are ultimately solar-derived: mainly solar energy itself, biomass resources and wind power. The energy resource input into the whole system is termed ‘primary energy’ and may be defined by:

$$\text{Primary energy} = \text{downstream end-use or delivered energy} + \text{upstream waste heat}$$  \hspace{1cm} (4)

Consequently, the overall performance of an energy system can be represented in terms of an efficiency:

$$\text{Overall energy system efficiency} = \frac{\text{energy supplied to final consumers}}{\text{primary energy consumed}} \times 100\%$$  \hspace{1cm} (5)

Despite significant changes in the fuel mix utilized within the UK energy system over the period from 1965 onwards, its overall performance has altered little (Hammond\textsuperscript{14}). The energy overheads (losses due to conversion inefficiencies and transmission losses) and overall system efficiency are given in Table 1. It can be seen that the efficiency for the supply to final consumers has varied by only some 2\% since the mid-1960s. This slight fall was primarily due to the greater use of electricity in the industrial sector, albeit supplied by new power plants with higher efficiency. Modern combined cycle gas turbine (CCGT) power stations have a thermal efficiency, for example, of 45–55\%\textsuperscript{14}.

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**Figure 3.** Simplified representation of the UK energy system [Source: Hammond\textsuperscript{1}].

**Table 1.** Overall performance of the UK energy system.

<table>
<thead>
<tr>
<th>Year</th>
<th>Primary energy consumed, PJ</th>
<th>Energy supplied to final consumers, PJ</th>
<th>Energy overhead, PJ</th>
<th>Overall energy system efficiency, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>8046</td>
<td>5662</td>
<td>2384</td>
<td>70.4</td>
</tr>
<tr>
<td>1975</td>
<td>8521</td>
<td>5893</td>
<td>2628</td>
<td>69.2</td>
</tr>
<tr>
<td>1985</td>
<td>8665</td>
<td>5940</td>
<td>2725</td>
<td>68.6</td>
</tr>
<tr>
<td>1995</td>
<td>9183</td>
<td>6318</td>
<td>2865</td>
<td>68.8</td>
</tr>
</tbody>
</table>

Abbreviation: PJ = petajoule ($10^{15}$ J).


Origin: Hammond\textsuperscript{14}, Table 3.
Indigenous Fuel Balances

In the immediate post-WWII period, most fossil fuel reserves were plentiful in the ‘West’ (the member countries of the Organization of Economic Co-operation and Development, OECD), with cheap petroleum supplies readily available from the Middle East. Solid fuel (coal, coke and breeze) was the main source of energy for home heating, in industry, and for electricity generation. Oil dominated the road transport sector, where it could not easily be substituted by alternatives, but also began to encroach on the domain of ‘King Coal’. It was coal that fired the economic recovery of Europe in the 1950s, which in turn led to increased imports of oil in order to match the demands of the ‘economic miracle’ (see Andrews5). The relatively high price of coal and moves to encourage the use of ‘smokeless’ fuel on environmental/health grounds, particularly in the home, induced coal/oil substitution in the domestic, industrial and services sectors.

The growth in global petroleum consumption throughout the 1960s contained the seeds of instability in the oil market, with two-thirds of supplies being imported from the Arab countries (see Andrews6 and Hammond14). The major destabilizing event occurred in October 1973, when Israel was attacked by its Arab neighbours in what became known as the Yom Kippur War. The Middle East members of the Organization of Petroleum Exporting Countries (OPEC) felt that the United States and some of its European allies had overly supported Israel. In retaliation Saudi Arabia imposed an oil embargo on the USA and the Netherlands, which ultimately led to a cut of 17% in OPEC’s output. This induced the first oil price hike or ‘shock’, with prices rising from US$3 per barrel to $11 over the period of a few months. The impact of these events was to engender a feeling of insecurity in Western industrialized countries, and they collectively started to introduce measures that would free them from effective dependence on OPEC oil supplies. These were co-ordinated by a new body, the International Energy Agency (IEA), established under the umbrella of the OECD. On the supply side, encouragement was given to the development of non-OPEC, particularly indigenous, sources of energy. This was coupled with a variety of energy efficiency measures. By 1985, these actions had been successful in ending the reign of OPEC as the oil price setter (at least until the dawn of the 21st Century).

Britain played its full role during this period, in consort with its partners in the IEA/OECD. In 1967 the UK commenced piping ashore natural gas from the West Sole field of the southern North Sea basin. It marked the start of a major investment programme, which accelerated throughout the 1970s, aimed at converting every gas-burning home from coal (or ‘town’) gas to natural gas. This eventually induced a major shift in consumer preference towards gas-fired central heating. Natural gas consequently increased its share of the domestic energy market from some 13% in 1965 to just over 65% by 1995 (see Hammond14). Development of North Sea oil during the 1970s and 1980s led to the UK becoming self-sufficient in petroleum supplies by 1981, as shown in Figure 4 (updated by Hammond1 from the original work of Hammond and Mackay13). This comparison of indigenous oil supply and demand was based on a skewed normal production profile for the UK continental shelf. The area beneath the projected supply curve represents the ultimate recoverable reserves, although Hammond and Mackay13 noted that these were heavily dependent on geological estimates which vary significantly over time. They employed data up to 1988, and Figure 4 therefore illustrates the short-term accuracy of their forecasts. In the intervening period oil demand has followed their projections quite closely, but North Sea production has outstripped the forecast.

The structure of the energy supply and distribution industries in the 35 years immediately following World War II was dominated by the notion that electricity and gas were ‘natural monopolies’. It was argued (see Hammond14) that it was not practical to lay more than one gas pipeline or electrical cable network. These monopolies gave rise to some benefits, as when British Gas was able to push through the conversion of the UK from town to natural gas, but also to disbenefits. In the case of the electricity supply sector the Central Electricity Generating Board (CEGB)
dominated the sector in England and Wales. It was given the aim by successive governments of producing electricity as efficiently as possible. This led to the preponderance of central-station plant, and to the neglect of demand-side efficiency issues. There was no incentive for the CEGB to try to improve the overall energy efficiency of its generation system by, for example, encouraging combined heat and power (CHP) plant. Likewise it displayed only a modest interest in distributed new and renewable energy technologies. Only with market liberalization after the 1980s and the recent climate change concerns have the prospects of serious alternatives in the energy sector been opened up.

Post-1970 projections for UK natural gas supply and demand are presented by Hammond. In this case the so-called ‘dash for gas’ has outstripped most contemporary predictions. Even the recent estimates of Hammond and Mackay, based on European Commission forecasts published in 1990, under-predicted by some 85% the electrical output of new CCGT plants in 1995. Thus, over the period 1992–1997 the dominant position of coal-fired power stations in UK electricity supply had changed dramatically from having held 60% of the market to only 33% in just 5 years. They had been overtaken by nuclear power plant as the largest generator with a 36% share, and were closely followed by natural gas which captured 29% of the market. This process has continued, as can be seen in Figures 5 and 6. The new Labour Government in Britain is currently restricting planning consent for new CCGT plant, although it looks more favourably on schemes that incorporate CHP.

**Electricity Use and Generating Plant**

Electricity is a high-grade energy carrier in the sense that it can be used to provide either power or heat. It is essentially a ‘capital’ resource that is normally generated in advanced, industrialized countries using either fossil or nuclear fuels (see Hammond). These latter sources may be contrasted with the renewable (or ‘income’) energy sources, such as solar energy and tidal, wave and wind power. However, large energy losses occur during generation unless used in conjunction with CHP systems. It is also wasteful in thermodynamic terms to convert fuels to electricity only to employ it for heating. If heat is required, then it would be far more efficient to burn fossil fuels (for example) to produce heat directly. Chapman discusses the relative end-use merits of electricity, arguing that (in spite of the lack of detailed statistics) it was possible to estimate that some 25–35% of electricity in the UK was used for heating in the mid-1970s. Lovins has suggested that in the USA only some 10% of final energy use requires electricity. In any case, the latter is a rather poor substitute in transport, which predominately uses petroleum products. The issue of substitutability of fuels in the transport sector is still one that is insufficiently addressed, given some of the projections for the short life of oil and natural gas.

In order to determine the primary energy inputs needed to produce a given output of product or service, it is necessary to trace the flow of energy through the relevant industrial system. Such a procedure is based on the First Law of Thermodynamics; the principle of conservation
of energy, or the notion of an energy balance applied to the system. It became known as energy analysis or accounting in the late 1970s, and has been used to determine the First Law (or energy) efficiency of UK electricity generation.

First Law energy analysis enables energy or heat losses to be estimated, but gives no information about the optimal conversion of energy. In contrast, the Second Law of Thermodynamics shows that not all the energy inputs into a system can be converted into useful work. It therefore provides the basis for the definition of parameters that facilitate the assessment of the maximum amount of work achievable in a given system with different energy sources. Exergy is the available energy for conversion from a donating source with reference to a specified datum; usually the ambient environmental conditions (typically 5–25°C). In a sense it represents the thermodynamic ‘quality’ of an energy vector, and that of the waste heat or energy lost in the reject stream. Second Law or exergy analysis is the only way of determining where the thermodynamic value of the source is lost in processes or in society. It provides a basis for defining an exergy efficiency, and can identify the ‘improvement potential’ within systems.

The privatization of energy utility companies in the 1980s and moves towards the creation of a fully competitive energy market have induced dramatic changes in terms of energy resources employed for electricity generation (Hammond; see also Tables 2–4). Relative fuel prices, construction costs and times, and arguably environmental benefits, led to the ‘dash for gas’ and a fall in the amount of indigenous solid fuel consumed at power stations (see also Figures 5 and 6). This took place at a time when there has been an international and national emphasis on the need to achieve sustainable development. The broad range of factors that therefore impinge on the choice of fuel or technology for power stations are summarized in Tables 2–4. These encompass both First and Second Law generation efficiencies, security and diversity of energy sources, and environmental impacts of one sort or another. Reconciliation of these conflicting factors is a complex matter that cannot readily be treated by formal methods. Rather than attempting to find an optimal solution, a pragmatic approach is required; what is often termed ‘satisficing’ in the management literature.

It can be argued (see, for example, Hammond) that the UK Government will need to keep the balance of energy resources under periodic review (perhaps with the aid of external advice), and intervene in the competitive energy market to offset its deficiencies. Similar views have been expressed by Ian Fells and his co-workers, albeit in a rather more robust manner. The UK Government has already moved some way in this direction within the electricity generation sector as indicated in the recent ‘White Paper’ on energy sources for power generation. It favours consent for the construction of CHP plant, which produce both electricity and useable heat, provided they are suitably sized to meet on-site or nearby heat requirements. Such schemes have an overall First Law efficiency of some 80% in contrast to the best CCGT plant of 40–50%. In fact, all the fossil fuel ‘power’ station designs have a high CHP potential (see Table 3). However, current UK Government action is only likely to be temporary. It aims to return the electricity supply industry (ESI) to a competitive market position once the current electricity trading arrangement, or ‘pool’, is reformed to

Figure 6. Solid fuel and oil inputs into UK electricity generation [Projections: hatched area, EP65 range and dashed line, DTI (2000)].
counter market manipulation by large generators. The Government will then have to rely on a range of alternative mechanisms to balance the diverse needs of a sustainable electricity supply sector. These include stricter consents on the construction of new power stations, the Renewables Obligation on electricity suppliers to provide 10% of their output from renewable sources by 2010, preferential treatment for CHP and renewables under the Climate Change Levy on businesses, and the latest Energy Efficiency Standards of Performance (EESOP 4) requiring electricity and gas suppliers to help domestic consumers to save energy.

Comparisons between the actual primary energy inputs into electricity generation in Britain, together with EP65 and DTI (2000) projections, are shown in Figures 5 and 6. Hammond noted that the corresponding intensity of electricity use was rather higher than anticipated during 1975–1995. This is somewhat in line with the arguments advanced by the UK Atomic Energy Authority (UKAEA) that, as a high quality energy carrier, electricity would secure a favourable end-use position in the market. The amount of electricity supplied to final consumers nearly doubled over the last 30 years, whilst the efficiency of generation improved from about 30% in 1965 to over 35% currently (see Hammond). This reflects the introduction of more modern plant, particularly CCGT power stations, and the ‘dash for gas’ for electrical power generation which is clearly illustrated in Figure 5. It was this element of the fuel mix that was not envisaged in the 1970s and 1980s; contrast Figures 5 and 6. The latter graph also shows the fuel switching between coal and oil during the 1984–1985 coal miners’ strike.

SUSTAINABLE DEVELOPMENT AND THE ENERGY SECTOR

Principles and Practice of Sustainable Development

In the aftermath of the 1992 Earth Summit in Rio de Janeiro (the UN Conference on Environment and Development) there has been a greater awareness of the need to devise strategies aimed at sustainable development (see Hammond); balancing economic and social development with environmental protection. The WCED in the influential Brundtland Report defined sustainable development as meeting ‘the needs of the present without compromising the ability of future generations to meet their own needs’. It therefore involves a strong element of intergenerational ethics. Many writers and researchers have acknowledged that the concept of ‘sustainable development’ is not one that can be readily grasped by the wider public. However, no satisfactory alternative has been found. John Prescott, the UK Deputy Prime Minister (with responsibility for the Department of the Environment, Transport and the Regions), has sometimes adopted the layman’s term ‘quality of life’ as a shorthand expression when referring to sustainable development issues applicable both to Britain and the wider world. However, the UK Round Table on Sustainable Development, amongst others, feels that the quality of life is only part of what is meant by sustainable development. It believes that it would be unfortunate if the two expressions became synonymous in the ‘public mind’.

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Table 2: Security and diversity energy sources for UK electricity generation.

<table>
<thead>
<tr>
<th>Resources</th>
<th>UK mines and imports</th>
<th>UKS/No/Norway (NKS)</th>
<th>Norway/No (NN)</th>
<th>N/A</th>
<th>N/A</th>
<th>N/A</th>
<th>Visual intrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Depositing fossil fuel</td>
<td>Solid fuel</td>
<td>Natural gas</td>
<td>Primary electricity</td>
<td>Virtual power</td>
<td>Renewable (e.g., wind power)</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>* Deepening fossil fuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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The UK Round Table was established by the last Conservative Government in 1995, and attempts to build a consensus between people of different views and responsibilities around the theme of sustainable development. It retains all-party support in Britain, and has produced many influential reports. One of the earliest attempted to define the criteria for a sustainable transport sector. It highlighted five key principles that underpin sustainable development:

- **The Precautionary Principle**: This suggests that in the face of a significant environmental risk, lack of scientific certainty should not be used as a pretext to delay taking cost-effective action to prevent or minimize potential damage.

- **The Integration Principle**: This recognizes that environmental requirements must be integrated into the definition and implementation of all areas of policy-making. The new Labour Government has taken significant steps towards putting environmental concerns at the ‘heart’ of policy formulation. ‘Green’ Ministers have been designated in most Departments, and a cross-party Environmental Audit Committee has been established in the House of Commons to monitor progress.

- **The Polluter Pays Principle**: Here it is asserted that those responsible for causing environmental damage should bear the costs of preventative or remedial action, and not society at large.

- **The Preventative Principle**: This suggests that in the long-run it is better for society to avoid the remedial costs of pollution and waste that can result from development activities.

- **The Participation Principle**: This recognizes that widespread and informal public participation is an essential prerequisite for effective decision-making in the area of sustainable development. The Round Table sees itself as very much part of this participation process.

The first four of these principles have been incorporated into European law in the Maastricht Treaty (Clause 130r), albeit in summary form. The intergenerational ethical injunction in the Brundtland report, effectively to avoid actions that might degrade the biosphere for future generations, presents special difficulties for the energy sector. It implies that governments should conserve depleting fuel resources, and make greater use of renewable energy sources. However, the World Energy Council suggested in 1993 that renewables might contribute between 3 and 12% of total commercial energy demand by 2020. A more recent study by the WEC, jointly with the International Institute of Applied Systems Analysis, has been rather more optimistic about the contribution of renewables after 2020. The greatest potential for renewable energy is likely to be in the second half of the next century, with the most optimistic supply projection being 80% of global demand by 2100. Nevertheless, uncertainties over the potential contribution of alternative energy supply-side technologies have led to a debate between the advocates of renewables and those favouring nuclear power. Both have argued that the concept of sustainability supports their widespread adoption. Thus, John Collier, the late Chairman of Nuclear Electric, and Robert Hawley, his former Chief Executive, have both suggested that nuclear power is one means of helping to maintain the energy resource balance of the planet at the same time as safeguarding its environmental quality. They had the issue of greenhouse gas emissions and global warming specifically in mind. On the other hand, Greenpeace argues that nuclear power will leave future generations with a legacy of nuclear waste. The two positions could, of course, be reconciled if an inherently safe nuclear fuel cycle could be assured, but this is difficult to prove a priori. Such a cycle would require safe and environmentally benign reactor plant and fuel reprocessing, as well as safe waste transport and long-term storage. However, this whole debate neglects the potential benefits of demand-side, or energy efficiency, measures discussed below.

### Fossil Fuel Resource Depletion

The combustion of finite reserves of fossil fuels results in their obvious depletion over time. It is often argued, particularly by economists, that the resource carrying capacity of the planet as a whole is so large that new discoveries offset current production. Although this may be true on a global scale, it is unlikely to apply at the level of the individual nation-state, or even at a regional level.
scale (such as within the European Union). There is considerable uncertainty over fossil fuel resources in the medium term. The lifetime and global distribution of these vary enormously:

- Oil: OPEC (Middle East)-dominated, 20–40 year life.
- Natural Gas: CIS (Russian)-dominated, 40–70 year life.
- Coal: Widely distributed, 80–240 year life.

These figures are rough estimates assuming current rates of consumption, but they indicate that the sources of fossil fuel supplies for OECD countries, with the exception of coal, are rather insecure. Slightly more precise estimates of the reserves to production (R/P) ratios are given in Table 2 as they apply to the UK, Europe and the World respectively. If depletion of oil and gas at anything like the rate indicated here actually occurred, then the price of these fuels would rise. The abundance of coal is likely to place an upper limit on all fossil fuel prices at the synthetic fuel cost for the foreseeable future. Nevertheless, this would make the financial case for renewable energy sources and nuclear power look much brighter. It has often been argued since the ‘oil crises’ of the 1970s that a nuclear power and/or renewable energy strategy should be adopted as an ‘insurance policy’ against the insecurity of the oil market. In reality these resources are not substitutable, particularly in the transport sector.

The resource base of the planet is not well defined; limits are often unclear until they are almost reached. One of the great challenges for the next century is therefore to improve dramatically the efficiency of resource use, particularly of non-renewable energy, across the planet so that humankind will ‘tread lightly on the Earth’.

Clearly the industrial nations, whose societies are by far the most resource-intensive, need to take the lead. A more equitable sharing of world income and resources is likely to be a prerequisite for long-term sustainability. It will require difficult decisions for the West in terms of market intervention to stimulate the development of sustainable technologies, and possibly to induce changes in life-style. These are matters of interregional and intergenerational ethics, rather than purely scientific debate.

In order to ensure sustainability of energy supplies, particularly in regard to the needs of future generations, it is necessary to conserve non-renewable resources in the medium term. Over a much longer time-scale, to around the turn of the next century, renewable energy sources may provide 80% or more of global demand. The current fuel mix in the UK is heavily dependent on fossil fuels, which are being depleted at a high rate; see Table 2. The R/P ratios for coal, oil and natural gas in Britain are all much lower than the global figures indicated above, and exhibit an alarming downward trend. There is still considerable uncertainty over the magnitude of indigenous reserves of oil and gas. Nevertheless, even with new discoveries (such as the West of Shetland or ‘Atlantic Frontier’ oil province), it is likely that the UK will soon return to the position of being a net importer with deleterious effects on the balance of payments, and economic growth generally. Certainly insufficient attention is being paid by British politicians to the consequences of the depletion of North Sea resources.
The Environmental Impact of Conventional Energy Technologies

The combustion of fossil fuels result in pollutants that can damage human health and the environment on a number of levels. Those that have possible impact on a regional or global scale are:\1.14:

- Global warming: greenhouse gases
  - carbon dioxide (CO\textsubscript{2})
  - nitrous oxides (NO\textsubscript{x})
  - water vapour (H\textsubscript{2}O)
- Global/regional cooling:
  - dust particulates; condensation nuclei
  - sulphate aerosols
- Regional acid rain precursors:
  - nitrous oxides (NO\textsubscript{x})
  - sulphur dioxide (SO\textsubscript{2})

Most environmental concern has recently focused on global warming\textsuperscript{4}. Thus, the speculative prospects of global climate change induced by the emission of so-called ‘greenhouse’ gases (GHG) from fossil fuel combustion is an issue of considerable interest. They are of particular concern to those Western European nations at risk of flooding if sea levels were to rise as a result of climate change\textsuperscript{1}. The critical issue is whether the observed global warming is due to human activity or simply a natural phenomenon induced, for example, by variations in solar output over decades. The UK Natural Environment Research Council\textsuperscript{46} has summarized the current state-of-the-art in climate change research. The British Government’s Chief Scientific Adviser, Sir Robert May\textsuperscript{47}, has advocated action to reduce carbon dioxide emissions on that basis of what environmentalists term the ‘precautionary principle’ (and discussed above). Not out of conviction that anthropogenic climate change is currently proven, but because its possible effects over the next century may be damaging and large-scale. Carbon dioxide released into the atmosphere from the burning of fossil fuels is thought to persist for around a 100 years.

Sustainability Indicators

The last Conservative Government in Britain (1990–1997) took active steps to incorporate the notion of sustainability into its general policy framework, including that for energy\textsuperscript{1,14,22}, albeit within the constraints of its free market philosophy. It defined the aims of energy policy as ensuring ‘secure, diverse, and sustainable supplies of energy in the forms that people and businesses want, and at competitive prices’\textsuperscript{48}. It undoubtedly succeeded in the major undertaking of developing energy market competition within a framework of law and regulation. The Ministers at the then Department of the Environment took a major step forward in publishing a preliminary set of sustainability indicators to stimulate debate and discussion\textsuperscript{17}. It proposed a consistent framework with interlinked packages of indicators covering sub-sectors of the economy. In most cases the primary indicators are normalized using an appropriate parameter reflecting activity levels, such as the number of households in the domestic sector. Within the energy area these are much the same as those adopted and discussed by Hammond and his co-workers\textsuperscript{1,14,20}. Primary and delivered energy consumption in each of the four demand sectors considered here were used as key indicators, together with the corresponding energy consumed per unit of output; similar to the energy intensity defined by equation (1). Associated pollutant emissions were also reported. Trends in the indicators over time were displayed (using 1970 as the base year for the energy sector), together with a commentary by the Department on perceived progress toward meeting sustainability objectives.

The new Labour Government elected in May 1997 has taken forward the process of embedding sustainable development into the ‘heart’ of its administration. Environmental and natural resources issues have been integrated into the development of policy, alongside economic and social ones. Something that is much in line with the UK Round Table’s ‘integration principle’. The aims of energy policy are formally the same as those adopted by the Conservatives, although concerns such as ‘fuel poverty’ have been given a higher profile\textsuperscript{48}. New Labour Ministers have given support to the preliminary set of some 120 sustainability indicators devised by their predecessors (and cited above\textsuperscript{22}), but have also argued for a smaller number of ‘headline’ indicators\textsuperscript{39} to be used to monitor progress, together with the original cluster of measures. It is a pity that no energy indicators are included in the initial set. A number of related measures have been selected for the menu of 10 indicators, such as those for climate change (emissions of CO\textsubscript{2} and a basket of GHG weighted by global warming potential), air pollution, and road traffic (billion vehicle miles for cars and taxis and ‘other vehicles’). Supporting information on energy consumption will also be given with the climate change indicators\textsuperscript{39}. The UK Round Table\textsuperscript{49} feels that the sustainability indicators should be made available at the level of Scotland, Wales and Northern Ireland, and the English regions, as well as UK-wide as originally proposed. It has also argued that research should continue on developing composite or aggregate sustainability indicators, like the ISEW, to be used in addition to the headline measures.

ENERGY MARKET COMPETITION AND SUSTAINABILITY

The introduction of competition into the British energy market has resulted in the decline of indigenous deep-mine coal production, and the rapid depletion of North Sea oil and natural gas reserves. The switch from coal to natural gas stimulated by energy market liberalization has had a favourable short-term effect on GHG emissions. Consequently, the post-Kyoto legally binding EU target of reducing a basket of GHG to 12.5% below 1990 levels over the period 2008–2012 will require only modest governmental intervention, over and above falls in emissions stimulated by energy market liberalization. The UK has a tighter domestic goal aimed at a 20% cut in carbon dioxide emissions below 1990 levels by 2010. CO\textsubscript{2} accounts for some 80% of the total GHG emissions\textsuperscript{11,12}, and the energy sector is responsible for around 95% of these. Recent trends in CO\textsubscript{2} emissions from this sector are shown in Figure 7, along with the anticipated reduction due to measures already included in the British Government’s Climate Change Programme\textsuperscript{12}. However, the Minister for the Environment has acknowledged that, in order to
stabilize atmospheric CO₂ at current levels in the long term, a 60% cut would be required from developed countries rather than the 5% agreed under the Kyoto Protocol (Michael Meacher in a talk to the Associate Parliamentary Engineering Group, House of Commons, 19 January 2000). The Royal Commission on Environmental Pollution has more recently argued that the UK should take the lead in adopting a target of reducing CO₂ emissions by some 60% from 1997 levels by about 2050. It presents four long-term energy scenarios employing this target, with various low-carbon options having differing proportions of nuclear power, renewable energy technologies, and energy efficiency measures. These are ‘normative’ scenarios in that they start by postulating what should be achieved in terms of CO₂ mitigation, rather than making any attempt to forecast the eventual outcome.

Hammond has argued that the ‘free’ market is unlikely to achieve a satisfactory balance between the broader requirements of sustainable development and environmental protection over the longer term. The short time horizon of markets means that they tend to ignore both the depletion of fossil fuels and the long-term potential for technological innovation; ‘pinch points’ often go unrecognized by commodity and stock markets until they are almost reached. In addition, energy prices do not account for ‘externalities’, including the environmental costs associated with damage to the natural environment and possible climate change. Although it is desirable to work with the ‘grain’ of the liberalized energy market, Hammond has suggested that governments need to intervene to offset its deficiencies (see also the similar views expressed by Fells and his co-workers). The two main candidates for intervention are economic instruments (carbon and/or energy taxes, and traded permits) and utility regulation in the wider interests of environmental protection. Bodies as diverse as the Royal Society for the Protection of Birds and the UK Round Table on Sustainable Development have now also advocated greater state intervention on environmental grounds. Important steps in this direction were taken in the Budget Statements of 1999 and 2000, when the Chancellor of the Exchequer announced the introduction of a ‘Climate Change Levy’ on the business use of energy, reform of the company car taxation regime to discourage extra business miles and provide incentives for more fuel-efficient cars, tax measures to promote non-car commuting, the use of bicycles and car-sharing, and additional funds to support rural transport. These are major developments aimed at shifting the burden of taxation from ‘goods’ to ‘bads’. They should eventually demonstrate whether or not economic instruments will have the effect of constraining energy use and pollutant emissions that their advocates suggest. The RCEP and others favour replacing the Climate Change Levy with a general carbon tax based on CO₂ emitted per unit energy supplied. This should be applied upstream, where fossil fuels are first purchased, and cover all sectors. The Royal Commission argues that carbon tax revenues should then be employed to reduce fuel poverty, invest in energy efficiency measures, increase the viability of other low-carbon energy alternatives, and to protect UK industrial competitiveness.

On the supply side, the full fuel cycle costs of gas-fired power stations are currently very low compared with those of their coal-fired counterparts (see Table 3). This was part of the reason for the so-called ‘dash for gas’ during the initial phase of energy market liberalization 1985–1997. In the aftermath of its review of ‘energy sources for power generation’ the Government decided to limit consent for building new gas-fired plant, except for CHP

![Figure 7. Carbon dioxide emissions from the UK energy sector.](image-url)
schemes. The strict consent regime will be maintained over an unspecified transitional period whilst a new electricity trading arrangement is devised that will remove ‘market distortions’. However, the eventual aim is still to encourage competition across the whole of the energy market in the interests of consumers, with only cursory attention being paid to the needs of sustainable development.

TOWARDS A SUSTAINABLE ENERGY STRATEGY

Living with Uncertainty: A Professional View

In the long run an ideal energy strategy in terms of environmental sustainability would be one that minimizes primary energy and electricity use, and maximizes the contribution from renewable energy sources. But the realities of market economics suggest that investors will go for a least-cost option in the absence of proactive Government intervention. This implies a major share of the energy sector for fossil fuels, particularly oil and natural gas, in the medium term (up to 2010, and possibly well beyond). It is therefore necessary to devise a transitional energy strategy appropriate to the conditions that are likely to prevail in the UK during the intervening period. This needs to be robust, and account for the uncertainties inherent in the energy field. The British engineering profession has been actively engaged in examining alternative energy technologies and strategies. Contributions have been made by working groups from the National Academies Policy Advisory Group (NAPAG) and the Engineering Council, who sponsored the Energy Joint Venture Study Group of the Engineering Institutions. These studies advocate a number of common elements of a transitional energy strategy. On the electricity supply side they support the development of clean coal technology, further construction of advanced CCGT plant, an increase in renewable energy, as well as a continued significant contribution from nuclear power. Controversially they argue for recycling plutonium in both thermal and fast breeder reactors. The latter runs quite counter to current UK Government energy policy. [Further discussion of the role of nuclear power can be found below.] Overall these learned society groups suggest that the aim should be a balanced and diverse portfolio of primary energy sources that recognize the UK’s indigenous resources. Energy conservation is seen as the most cost-effective means of CO\textsubscript{2} abatement. In the academic literature there has been some debate over whether or not there is a ‘rebound effect’ induced when consumers invest in energy efficiency measures (see, for example, Herring). Some economists have argued that a significant proportion of energy saving is taken back in the form of higher, and less efficient products. However, it would appear that the effect is small, as the primary energy intensity (kWh/£1990) in the UK has generally fallen since 1965 (as shown in Figure 2).

In practical terms, the NAPAG energy working group called for the encouragement of energy-saving by the Government use of energy price signals, via taxes or regulation. It argues that these prices should reflect more closely their full social and environmental costs. The UK Government recently embarked on such an approach (as noted above). The NAPAG working group believes that a reduction of more than 20% in UK energy demand is achievable over the next 20 years with readily available, existing technologies. Both it and the Engineering Council group stress the importance of tackling the road traffic problem. Because of the increasing dominance of transport energy use in the UK energy balance, the energy options in the transport sector are discussed in some detail below.

Second Law Analysis: Identifying Priorities

The exergy method has recently been used by Hammond and Stapleton to examine the Second Law performance of the UK energy system. This was achieved by disaggregating the economy on a broad sectoral or ‘macroscale’ basis (like that implied by Figure 3), following that previously adopted by Hammond for First Law analysis. The particular characteristics of each sector were then utilized in order to estimate sector-weighted or ‘lumped’ parameters, such as averaged exergy efficiencies. These indicators were then employed to determine the exergetic ‘improvement potential’ in the main sectors. Hammond and Stapleton found that the only way to improve significantly the ESI energy efficiency, in the absence of new large-scale hydropower sites in the UK, is either to restrict the use of electricity to power applications (and not for relatively low temperature heating), or to adopt a greater proportion of CHP plants. On thermodynamic grounds the rank order for the construction of new fossil-fuelled power plant would therefore be CHP or cogeneration schemes, CCGTs, and integrated coal gasification combined cycle (IGCC) plants, reflecting the highest to lowest conversion efficiencies respectively.

Energy end-use in the domestic sector has displayed fuel switching from coal to natural gas on quite a large scale since 1965 (see, for example, Hammond). At that time, less than 10% of households had central heating, compared with over 80% now. The underlying modest growth of some 15% in final energy demand within this sector over time (see Figure 8) is primarily the result of an increase in the number of UK households. Fluctuations about this trend are caused by variations in year-on-year weather conditions; the driver for space heating. Improvements in heater efficiency and in thermal insulation standards have both significantly held down energy consumption when compared to a ‘business-as-usual’ scenario. The upward trend in the use of so-called ‘white goods’ or domestic appliances has had only a moderate impact on final demand, which is dominated by space and water heating. In any case it is often argued that saturation effects in the ownership of such appliances will inevitably take place in the near future. Hammond and Stapleton found that the overall domestic sector exergy efficiency was only some 13% in the mid-1990s, whereas the corresponding energy efficiency was a little over 60%.

Delivered energy to the service sector of the UK economy has grown by some 45% over the period from 1965 onwards (see Figure 8). Commercial and public buildings encompass a greater diversity of types than in the domestic sector, including commercial offices, education, health, hotel and catering, retail and warehouses. These imply large differences in the energy intensity or ratio (energy consumed per unit of output) between end-uses. High energy intensities are, for example, found in hospitals that operate on a ‘round the clock’ basis. At the other end
of the spectrum, little space heating is required for product storage in warehouses. Nevertheless, the overall service sector energy intensity is considerably lower than in industry. Space heating exergy losses dominate the commercial and institutional sector to an even greater extent than in the domestic one\textsuperscript{29}. Significant opportunities exist for space heating energy savings via the adoption of new technologies\textsuperscript{14}, such as more efficient heating systems, higher thermal insulation standards, improved lighting systems and better environmental control. However, their introduction must rely heavily on the retrofitting of existing buildings, as there is a relatively slow turnover of building stock.

The industrial sector of the UK economy is the only one to have experienced a significant fall of roughly 40\% in final energy demand since the first oil price shock of 1973/74 (see Figure 8). This was in spite of a rise of over 40\% in industrial output in real terms. Consequently, the sector as a whole has seen a dramatic improvement in energy intensity; the primary cause of the drop in energy ratio for the economy as a whole (see Hammond\textsuperscript{14}). But this masks different underlying causes\textsuperscript{14,50}:

- **End-use efficiency:** It has been estimated\textsuperscript{50} that around 80\% of the fall in the industrial energy intensity between 1965 and 1995 was induced by the price mechanism\textsuperscript{14}.
- **Structural changes in industry:** The relative size of the industrial sector has shrunk with a move away from heavy industries\textsuperscript{14}, particularly in manufacturing and mining.
- **Fuel switching:** Coal use in UK industry has declined steadily since the early 1960s in favour of ‘cleaner’ fuel\textsuperscript{14,29}. Oil use also fell rapidly from 1973 onwards, with a couple of definite step changes associated with the two oil price hikes. Both natural gas and electricity consumption have increased to a market share of 25 and 33\% respectively\textsuperscript{14}. They are cleaner, more readily controllable, and arguably cheaper for the business concerned.

Hammond and Stapleton\textsuperscript{29} found that the overall industrial sector exergy efficiency (\textasciitilde46\% in the mid-1990s) is much lower than the corresponding energy efficiency (\textasciitilde69\%), although the disparity is not as large as in the domestic sector, where space heating requirements predominate. Nevertheless, there is still considerable scope for thermodynamic improvements in industry.

Final energy demand for passenger and freight transport in the UK has grown by 110\% over the period from 1965 onwards (see Figure 8); an annual rate equivalent to some 4\% per year. This roughly matches the increase in road traffic\textsuperscript{14}. It accounted for one-third of total end-use consumption in the mid-1990s, although only for about 20\% of primary energy demand\textsuperscript{29}. This is because electricity, with its poor conversion efficiency, plays a relatively small part in powering transport vehicles; principally half the delivered energy for trains. Rail transport in mainland Britain declined significantly in the late 1960s, although its final energy demand has remained fairly constant in real terms since then. Petroleum products of various kinds now dominate the transport sector, with an overall end-use share of some 99\%. The sector as a whole has a poorer thermodynamic effectiveness than either power generation or industry. Road transport and petroleum-fuelled combustion engines offer the principle scope for exergetic improvement in the coming decades.

For the UK in the late 1990s, Hammond and Stapleton\textsuperscript{29} found that final demand in the domestic and transport sectors, together with electricity generation, account for nearly 80\% of Second Law improvement potential. In order
to achieve large efficiency gains, it will be necessary to focus attention principally on making better use of space heating systems, improving the operating efficiency of ‘power’ plant, and reducing thermodynamic losses in transportation systems that are presently dependent on internal combustion engines. The sort of thermodynamic analysis used by both chemical and mechanical engineers can therefore make an important contribution to identifying opportunities for process improvement.

The Nuclear Option

The first commercial nuclear power plants were constructed in the 1960s. Electricity generation using this technology has now spread internationally to such an extent that some 30 countries operate nuclear power stations. However, by the 1980s people in the West became far more aware of the possible disadvantages of nuclear power. Two events reinforced this perception: the reactor failure at Three Mile Island (USA) in 1979 which was contained, and that at Chernobyl (USSR/Ukraine) in 1986 which was not. In addition, many people became concerned about handling radioactive materials, principally radioactive emissions during the fuel cycle, the subsequent disposal of high and intermediate-level waste and decommissioning of plants would require facilities which would operate safely over many decades. Another factor that discouraged nuclear power development is that the prospect of cheap nuclear energy seemed much less certain than had been claimed by its early advocates. The capital costs are high and they have not been offset by low running costs, particularly if waste disposal/storage and decommissioning (or ‘back-end’) costs are taken into account. The private sector has generally proved unwilling to meet these liabilities without government financial support in one form or another.

The gloomy aspect for nuclear electricity generation in the 1980s was partially transformed in the 1990s. This came about owing to the realization that there may be serious global environmental consequences of the continued burning of fossil fuels. In addition to the problem of pollutant emissions from fossil fuel combustion, there is also now a better awareness (by opinion formers) of the finite nature of oil and natural gas reserves. It has often been argued over the last few decades that nuclear power should be adopted as an insurance policy against the insecurity of the oil market. In order to meet the special demands of the transport sector, the electricity generated would need to be used, in part, to produce a substitutable fuel like hydrogen.

The Royal Society (RS: the British academy of science founded in 1660) and its much younger cousin, the Royal Academy of Engineering (RAEng), recently established a joint working party to examine the role of nuclear energy in generating electricity, but set against a background of a range of alternatives to conventional fossil fuel power stations. They took the potential threat of anthropogenic or human-induced global warming as the main energy sector ‘driver for change’. Members of the working party argued in their report that it is unlikely that a combination of energy efficiency measures, new or renewable energy technologies, and methods for carbon sequestration, will together meet energy demand in the next two decades, while simultaneously restraining the emission of greenhouse gases (GHG). They consequently recommended that the nuclear energy option should be kept open because it, like renewables, produces negligible GHG emissions (see Table 4). Although plant lives may be extended from their typical 25 year design life to nearer 40 years. Britain will progressively need to decommission its older nuclear power stations during the next decade or so. This will leave only the Sizewell 'B' PWR station, with nuclear power holding a considerably reduced share of electricity generation (perhaps as low as 3% by 2020 from the present 24%). In order to maintain the current nuclear output, the RS/RAEng working party noted that five new twin-reactor PWR plants (having a total installed capacity of 12.5 GWe) would need to be commissioned in the UK over the period 2009–2017. Government approval for their phased construction starting in 2003 would therefore be required shortly after the next General Election. This argument has been criticized by Hammond on the grounds that it neglects the results of the sort of Second Law analysis described above (which favour energy efficiency, and render the choice of new power generation plant a peripheral issue), and the poor cost competitiveness of nuclear power in the liberalized energy market. Nuclear plant exhibit high life-cycle costs, as indicated above, when ‘back-end’ costs are taken into account. Energy efficiency measures currently displace between 2.5 and 20 times more carbon dioxide than would new nuclear power plant per dollar invested.

Over a longer time horizon, it is likely that UK Government officials will want to keep a watching brief on emerging nuclear reactor designs (currently being developed in France/Germany, South Africa and the USA) that may prove to be inherently safer and less costly; perhaps having a 25% lower generating cost than present systems. Such developments were outlined in the RS/RAEng report. Nevertheless, the Government will no doubt want to be reassured that such new technologies, which might be commercially available in 10–15 years, are proven elsewhere before approving their construction in the UK. Their adoption would be critically dependent on public attitudes to nuclear power. In this regard, the Royal Commission on Environmental Pollution argues that considerations of inter-generational equity (embedded in the concept of sustainable development discussed above) demand a solution to the nuclear waste storage problem. It recommends that action is taken to design and construct an effective long-term repository for high-level and intermediate-level wastes as soon as practicable. Members of the RCEP believe that this should be done to the satisfaction of both the scientific community and the general public before any new nuclear power stations are built.

Renewable Energy Technologies

In order to secure credibility for its energy policy, the UK Government will have to reconcile the conflicting requirements of competition and environmental sustainability in the longer term. Renewable energy technologies will then need to play a substantial role; a conclusion also drawn by the RCEP. The Government’s recent consultation on renewable energy sources recognized the institutional and market barriers that might inhibit the attainment of their
ambitious renewables’ target; that these sources provide 10% of UK electricity by 2010. It is anticipated that the new Renewables Obligation, exemption under the Climate Change Levy, increased renewables R&D funding, and energy market reforms, will enable these new energy technologies to compete more effectively. Such an enhanced programme is clearly desirable in terms of helping to limit the depletion of indigenous fossil fuel resources and environmental protection, particularly CO₂ mitigation (see Figure 7).

Hydropower and wind turbines have high thermodynamic efficiencies; the former being around 65–75%²⁸,³⁵. Unfortunately the UK has already exhausted all its favourable sites for large-scale hydropower and pumped storage schemes. Although there are many suitable locations for onshore wind energy generators in the British Isles, they are meeting significant community resistance at local planning inquiries due to their perceived effects of landscape disruption and noise emission. The utilization of offshore wind turbine arrays may avoid these difficulties, but only at higher life-cycle financial costs. Both offshore wind ‘farms’ and the growing of energy crops (biomass) as a primary use for agricultural land have recently been given a strong endorsement by the RCEP as possible long-term energy options. Solar energy systems, such as modern grid-connected photovoltaic devices, are diffuse and have low conversion efficiencies compared with their 5500 K potential. Nevertheless they are renewable rather than depletable energy resources. Consequently, Lovins²⁷ has argued that renewable energy in general should be viewed as having a premium over fossil fuels and uranium, with their finite life. Hammond and Stapleton²⁹ argued that for this (and other) reasons primacy should not be given to the results of Second Law exergy analysis.

Current UK electricity generation from renewables (with and without large-scale hydropower plants) is shown in Figure 9, together with DTI (2000)¹¹ projections to the 10% target. The Institution of Electrical Engineers (IEE) has raised serious doubts about whether the UK national electricity grid is capable of handling this proportion of power supplied from dispersed renewable sources (in evidence to the Government’s consultation on new and renewable energy⁵⁵). It argues that power quality cannot be guaranteed without overall co-ordination of power supply and distribution. Consequently, means need to be devised to bring small embedded generators as a group into a new system control structure. On engineering grounds the IEE believes that only some 7% of electricity demand could be met from renewables by 2010. These professional concerns reflect, in part, a traditional view of the electricity system based on supply from large central-stations⁸. It has recently been challenged by Patterson⁵⁵, who has postulated a range of alternative futures that could lead to the transformation of electricity systems. Under such a scenario power
might become in large measure decentralized. Much will depend on the extent of energy and electricity use efficiency improvements over the next few decades. The RCEP\textsuperscript{4} has recommended that the government should take the lead in a fundamental review of how electricity networks can accommodate large contributions from both renewable sources and CHP schemes. These networks will need to be financed, managed and regulated by 2050 in such a way as to maintain the reliability and quality of electricity supplies\textsuperscript{4}.

It remains to be seen whether the Government’s target for renewables can be met within a competitive market framework. There appears to be little prospect, for example, of large-scale projects being funded via this route. Even the proposed 8.6 GW Weston-Super-Mare to Lavernock Point tidal barrage scheme, which could meet some 6\% of UK electricity demand (albeit with potential ecological damage to the Severn Estuary), has not attracted serious investors under present market conditions, due to high capital costs and long construction periods. However, the RCEP\textsuperscript{4} recommends that the Government keep tidal barrages and in-current turbines under consideration as long-term options. Ministers are aware that the main contribution of renewable energy sources may well be in the period after 2016\textsuperscript{54}. They will certainly be needed if anything like a 60\% reduction in CO\textsubscript{2} emissions over the 1997 levels is to be achieved.

**Energy Efficiency: Factor 4 or More**

There is obviously a need to stimulate improvements in resource use efficiency generally, and to encourage energy conservation from ‘bottom-up’. Such an approach would need to be coupled with measures to reduce the rate of consumption of fossil fuels, and stimulate an expansion in the use of renewable energy sources\textsuperscript{4}. It would involve a consumer-oriented market approach, coupled with intervention by way of a portfolio of measures to counter market deficiencies; economic instruments, environmental regulation, and land use planning procedures. Scenarios such as the ‘dematerialization’ or ‘Factor Four’ project advocated by Ernst von Weizsacker and Amory and Hunter Lovins\textsuperscript{56} suggest that economic welfare in the industrial world might be doubled while resource use is halved; thus the Factor 4. This would involve a structural shift from energy intensive manufacturing to energy frugal services\textsuperscript{51}. Britain has moved some way in this direction (see Figures 2 and 8), with a 40\% improvement in primary energy intensity since 1965. Increases in resource use efficiency at the Factor 4 level (and the UK Foresight Programme is contemplating Factor 10 over the long term) would have an enormous knock-on benefit of reducing pollutant emissions that have an impact, actual or potential, on environmental quality. In reality such a strategy requires a major change (‘paradigm shift’) to an energy system that is focused on maximizing the full fuel/energy cycle efficiency, and minimizing the embedded energy in materials and products by way of reuse and recycling\textsuperscript{1}. In order to make such an approach a practicable engineering option, it would be necessary to use systems analysis methods to optimize the energy cascade\textsuperscript{1}. Thermodynamic analysis will be an important technique for identifying process improvement potential.

The potential importance of the global warming problem in many minds has resulted in the case being made for a ‘low carbon’, rather than just a ‘low energy’ economy. Technologies for carbon sequestration have therefore been identified as an important element in any energy R, D & D programme. Such approaches are certainly consistent with the ‘precautionary principle’. Japanese industry (see, for example, Tsuge and Matsuo\textsuperscript{5}) is well advanced in terms of demonstration plant for CO\textsubscript{2} sequestration, as well as for other pollutants. Integrated coal gasification combined cycle (IGCC) plants lead to both relatively high thermal efficiencies (greater than 50\%) and a reduction of CO\textsubscript{2} of better than 20\% compared to conventional plant. In the case of clean coal technology, pressurized fluidized-bed boilers yield high combustion efficiencies together with NO\textsubscript{x} emission control. Here in the UK the Natural Resources and Environment Foresight Panel\textsuperscript{58} has called for research on a number of key carbon sequestration technologies.

The agenda for low-energy design concepts in road vehicles has arguably been set by Amory Lovins with his vision of a ‘hypercar’ (see Weizsacker et al.\textsuperscript{56}). This vehicle, termed ‘supercar’ in the original report, was postulated as being able to leapfrog incremental design improvements by adopting next generation technologies from other advanced industries. Thus, the hypercar would have an ultra-light, aerodynamically-shaped body fabricated using composite materials. It could utilize a hybrid power train in the form of a small (petrol or perhaps diesel) engine that would power electric motors at the wheels. Lovins argued that such a combination might lead to fuel efficiencies of up to 360 mpg but with the performance of top BMWs. This hypercar concept has been influential outside USA. In the UK it stimulated the Transport Technology Foresight Panel\textsuperscript{59} to advocate the development of a ‘Foresight Vehicle’ that is significantly more environmentally-friendly than current designs, but which meets mass market expectations in terms of cost, performance and safety. The Panel suggested that a range of motor car power systems could be encompassed within the development programme, including clean fuel internal combustion engines as well as electric and hybrid drives (collectively termed ‘low emission vehicles’).

Actions taken to reduce pollutant emissions from power stations, road transport, industry and in the home would have benefits on both a local and global scale. Measures to limit acid rain precursors from electricity generation, for example, will also reduce GHG emissions. (The power plant emissions displayed in Table 4 support this argument.) Similarly integrated transport strategies, currently being advocated by the UK Government, will alleviate congestion in urban areas, reduce toxic vehicle emissions (thereby improving local air quality and health), as well as mitigating the enhanced greenhouse effect. Policies of this type are therefore of a ‘win-win’ nature. They can be used to focus attention on local and regional environmental concerns to the benefit of ordinary people. Community participation can be encouraged via the Local Agenda 21 process that has been successful in many parts of the UK and elsewhere. It will encourage people to ‘think globally, act locally’ in a meaningful way. Central government needs to encourage implementation, and develop an enhanced systems modelling capability to ensure that the sum of the parts meet national targets\textsuperscript{1}.  

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Thus, the environmental challenges of the new millennium could be met with a mixture of vision and realism.

CONCLUDING REMARKS

There are various ways in which the energy system interacts with the requirements of sustainable development, encompassed in The London Communiqué². A strict interpretation of the Brundtland Commission injunction² would mean a rapid changeover to renewable energy, and the conservation of non-renewable sources (fossil fuels and uranium). This in turn could lead to a significant reduction in pollutant emissions, the unwanted or side-effects of the energy sector, that have a damaging impact at a local, regional and global scale. Only in this way could the biosphere be protected for future generations. However, dramatic changes to the nature of the energy system appear unlikely in the short to medium term. Current UK measures to combat climate change will reduce CO₂ emissions (see Figure 7) to the domestic target of a 20% fall below 1990 levels. But this is a modest achievement compared with the perceived global need to reduce GHG emissions by some 60% to stabilize the climate. The Royal Commission on Environmental Pollution recently advocated that the UK should adopt a target of reducing CO₂ emissions by 60% from 1997 levels by about 2050. They devised four normative energy scenarios on this basis, using various low-carbon options with differing proportions of nuclear power, renewable energy sources, and energy conservation measures for the long term. A robust transitional energy strategy is clearly required with a focus on energy efficiency (a move in the direction of Factor 4 or more technologies), and minimizing significantly pollutant emissions. The elements of such a strategy will change over time, and the ‘optimal’ mix at any given instant will be uncertain when viewed from the present. Engineers have much to contribute in terms of identifying opportunities for process improvement using thermodynamic and other means of analysis. Various medium-term energy options for the UK have been described here, along with the challenges they pose for the engineering profession.

A looser interpretation of sustainable development can be obtained from the so-called sustainability equation (2), or its corresponding energy and pollutant emission equivalents (equations (1) and (3), respectively). For a country like the UK with a near-constant population density, environmental protection could be sustained with modest economic growth provided the energy intensity and pollutant/energy ratio both fall. This has been achieved to some degree over recent decades (see Figures 2 and 7). Balancing economic growth in terms of traditional GDP per capita with measures for social and environmental improvement would result in an upward trend in indices of ‘real’ human development, such as the ISEW¹⁹ (see Figure 1).

The present work has primarily focused on energy-related considerations in the UK. It is certainly important that developed countries play their full part in maintaining environmental sustainability as they currently emit the bulk of pollutants into the atmosphere. But sustainable development must also be viewed in a global context. The task facing the nearly 80% of the world population that live in developing countries is daunting. They have, in most cases, rapidly growing populations which will drive up energy consumption and environmental pollution. This will feed back to the whole planet, and thereby alter the climate in the wealthier nations. Consequently they need assistance from industrial countries to promote Third World economic growth (which will, in time, induce a ‘demographic transition’¹²) and improve their energy systems. Economic development would benefit from, perhaps even require, fairer terms of trade between the OECD and developing countries. Environmental sustainability could be aided by the transfer of best practice energy technologies from the richer to poorer regions. This will ultimately be in the interests of all the citizens of ‘Spaceship Earth’.

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The author’s research on energy systems and environmental sustainability has been supported by research grants awarded by the UK Engineering and Physical Sciences Research Council (most recently under grants GR/J92910, GR/L02227 and GR/L26858). He would also like to acknowledge the support of British Gas plc (now demerged as BG plc and Centrica plc) who have partially funded his Professorship. However, the views expressed in this paper are those of the author alone, and do not necessarily reflect the policies of the company. He is particularly indebted to his Faculty colleague Barry Crittenden, Professor of Chemical Engineering at Bath, whose encouragement led to the writing of this paper. His colleagues Marcelle McManus and Richard Pannett, as well as two anonymous referees, provided helpful comments on an earlier draft. Finally, the author is grateful for the care with which Sarah Fuge and Heather Golland prepared the typescript and Gill Green prepared the figures.

ACKNOWLEDGEMENTS

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The manuscript was received 16 April 1999 and accepted for publication after revision 29 June 2000.

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