# Energy: The Long View

“The further backward you look, the further forward you can see” (Winston Churchill[1])

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[1] The quotation is commonly ascribed to Winston Churchill, although there is no clear source.

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## 1. INTRODUCTION

This paper looks at some long-term aspects of energy supply and use over the periods before and since the industrial revolution. It is intended to provide an overview and draw out some issues which deserve more sustained examination, not to give a definitive or comprehensive coverage of such a wide field. The rationale for the study is explained further below. If we are concerned about the long-term sustainability of our energy systems, we need to be able to think about energy from a longer-term perspective. This may mean revising some of our standard assumptions and expectations, which are often based primarily on experience with today’s energy markets.

The paper is divided into five sections, including:

- a brief discussion of the *rationale* for the paper and of some of the *methodological issues* involved (section 2);
- a snapshot picture of the *pre-modern energy economy*, particularly in Europe, where the industrial revolution started (section 3);
- a discussion of global *trends* in energy *since the industrial revolution* (section 4);
- an examination of some questions and *issues* arising from the analysis (section 5); and
- conclusions (section 6).

## 2. RATIONALE AND METHODOLOGICAL ISSUES

Economists, and perhaps particularly energy economists, tend not to take the long view. To many, the idea recalls only Keynes' comment that "In the long run, we are all dead" (1923), and by implication it is not something we should get very concerned about or is of much relevance. (Keynes prefaced his comment with the remark that "Long run is a misleading guide to current affairs".) Another approach is to tame the concept by limiting its scope; long-run marginal costs differ from short-run costs essentially by including capital investment. Similarly, analysis of energy trends whether past or future tends to deal with relatively restricted timescales of a generation or so. International Energy Agency (IEA) and US Energy Information Administration (EIA) energy projections normally cover a period of 25 years or less. Of 20 articles in the journal *Energy Policy* in 2007[2] which claimed to be dealing with the long term, the majority dealt with a period of 20 or 25 years (back to 1980 or forward to 2030). Only one article discussed a period of more than fifty years into the past or future, and that was in connection with nuclear waste disposal.

The reasons for this self-restraint are not hard to identify. Apart from doubts about the relevance of the long run to today's decision-makers, the normal raw material for economic analysis is usually not available for the distant past (or future) and the methodological problems in dealing with such data are acute, as discussed below. Relatively little attention is given to the distant past and to long-term economic and energy trends; only a few experts deal with such questions (e.g. Angus Maddison) and their work is often motivated by personal interest.

The subject matter of this paper – long-term energy trends – may therefore require some justification. The exercise may be regarded as both too academic in Keynes' sense (i.e. of no relevance to today's concerns) and at the same time insufficiently academic in another sense (i.e. incapable of robustness and rigour because of the methodological and data difficulties). However, while looking backwards over long periods may still be relatively rare, looking far forward has become more common and more important in a world increasingly concerned about long-term sustainability. In the spirit of Churchill's dictum, quoted on the title page, we ought therefore to be looking back as well as forward, in order to see forward more clearly.

This is particularly important in relation to climate change – perhaps the biggest challenge facing the world today and certainly one with the longest-term impacts. Climate change is inextricably linked with the energy sector, the main source of anthropogenic greenhouse gases. It requires us to look forward over periods of not just one generation but several centuries. For instance, the recent report on *The Economics of Climate Change* by Nicholas Stern (2007) contains forecasts of cumulative $CO_2$ emissions up to 2300. In discussing the costs and benefits of action to mitigate climate change, the report considers the impacts over many future centuries. Indeed, it gives considerable weight to those distant costs and benefits, a source of criticism from some quarters who point out that the conclusions are "driven by estimates of damages in the period after 2200" (Nordhaus, 2007).

The climate change debate raises the question of how we should think about the world's energy system many decades or centuries into the future. At the very least, we have an obligation to examine in a careful and rigorous way what might happen in "deep time" (as

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[2] *Energy Policy* volume 35, issues 1–10.

Paul Krugman described Angus Maddison's investigations into the past[3]). We need some basis for critical questioning of what aspects of the energy system are likely to be of permanent significance and what are merely contingent features at a particular stage of development, in order to ensure that we are not simply extrapolating short-term trends. Looking at the past will not give us all the answers, of course; what it may do is raise questions about the role of energy and help us examine and clarify the assumptions we make about the drivers of the long-term energy future.

This paper sets out to provide an introduction to some of the issues involved, primarily by asking what can be learned from the major transition which took place in the energy system between the periods before and after the industrial revolution.

### *2.1 Methodological issues: data*

The first and most obvious problem in investigating the transition is the lack of data. Before the industrial revolution, economic data were not gathered on a consistent or regular basis. Even basic population data are only available from official sources in the UK after the first census in 1801 (other countries started counting their populations at different stages). Official data on UK GDP only go back to 1938. Some data are available on output in earlier periods, of course, but they tend to be patchy. For the nineteenth century, they relate mainly to the new industries at the heart of the industrial revolution. For instance, reasonably good information is available for the production of and trade in coal or in relation to rail transportation. However, data about the traditional service sector and agriculture are patchy or non-existent, particularly in the first part of the century.

This is not just a matter of history; it is a continuing problem in relation to energy itself. Traditional sources of energy such as the biomass collected by local communities are generally omitted from recorded data, although they are still a significant energy source at a global level (and were of course the primary or sole source at the beginning of the industrial revolution). This can be a significant distortion. Data which show an increase in energy use with industrialisation, for instance, may be reflecting a shift in energy use from traditional non-traded sources to modern commercial energy. Estimates of non-traded energy use are essential to give an accurate picture of energy consumption in traditional societies. However, in the absence of regular official data they generally have to be calculated from a number of sources of varying value and consistency, such as detailed local histories; accounts of institutions such as monasteries and palaces or Poor Law administrators; and tax collection data.

### *2.2 Concepts*

Even if data can be identified or estimated, we need to consider whether we have an appropriate conceptual framework for handling them. In the wider economic sphere, for instance, there is some debate whether concepts such as GDP are relevant to, say, fourteenth-century England, where only a small proportion of output was traded. As with non-commercial energy, the problem is not solely historical. Many non-traded services are still not included in GDP figures today (e.g. housework performed within the household). In traditional societies where most output was not traded, decisions about what should and should not be included in the analysis and calculations become critical and this may apply

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[3] In a review of *The World Economy: A Millennial Perspective* quoted on the OECD web-site.

with particular force in the energy sector. It affects some of the key analytical tools with which we are familiar today. For instance, energy efficiency, energy intensity, carbon intensity, load factor and others are all problematic as units of measure in relation to the distant past. Indeed, the very concept of energy in its modern sense only came into use in the early stages of the industrial revolution;[4] a medieval commentator would not have recognised the term or the idea.

### *2.3 Relevance*

Finally of course there is the question of relevance. "The past is another country; they do things differently there" (Hartley, 1953) is true of energy as of other areas. Some would conclude from this that it produces no useful information for the present, as Keynes apparently did. However, this argument could be turned on its head. It is precisely because they do things differently in the past that we can use information from the past to start to examine how different things might be in the future. It is well recognised that forecasting in the energy sector is not easy, even over the relatively short periods of a generation or so with which projections such as those of the IEA and the EIA are usually concerned. One comparison of such forecasts concluded that "long range [sic – the reference is to the EIA and similar forecasts, which generally cover a period of 20 years or less] forecasters of energy affairs have missed every important shift in the past two generations" and "with rare exceptions, medium and long range forecasts become largely worthless in a matter of years".[5] If this is true of such relatively short time periods, then we need to consider how much useful information projections extending over hundreds of years can provide. We cannot, of course, forecast future trends by looking at the past. However, we can at least get some measure of the sorts of changes that might occur and how different the energy sector might look over long time periods. In other words, the distant past might be more relevant to the distant future than the present, precisely *because* they do things differently there.

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[4] According to the Oxford English dictionary, Thomas Young was the first to have used the term in this way, in his *Course of Lectures on Natural Philosophy*, 1807.

[5] Vaclav Smil cited in Winebrake and Sakva (2006).

## 3. THE PRE-MODERN EUROPEAN ENERGY ECONOMY

Because of the data limitations and other methodological problems described in the previous section, it is not possible to deal with trends in energy use before the industrial revolution in a quantified way, although we know that there were such trends, such as the introduction and deployment of windmills from the twelfth century on (Smil, 1994). Instead, this section will look at the broad outlines of the energy system in pre-modern western Europe. No precision is claimed for the estimates, which are drawn from a variety of authors (Braudel, 1981; Fouquet and Pearson 1998; Warde and Lindmark, 2006). However, there is broad agreement between the different sources, suggesting that the data represent a broad consensus and probably reflect the main features of the situation.

### *3.1 Energy balance*

Table 1 shows a rough estimate of the energy balance for Europe before the industrial revolution (approximately 1800 in most countries, although rather earlier in Great Britain). The figures are given in terms of power (where Mhp is short for million horse power and one horse power is equivalent to approximately 0.75 kW) rather than energy, as discussed below.

**Table 1. Energy balance for pre-modern Europe**

| Power source | Available capacity (Mhp) | Approximate share (%) |
|---|---|---|
| Animal traction | 10 | 50 |
| Wood | 4–5 | 25 |
| Water | 1.5–3 | 12.5 |
| Human | 0.9 | 5 |
| Windmills | 0.5 | 2 |
| Sail | 0.25 | 1 |

Source: based on Braudel, 1981.

In addition, there would have been small but increasing amounts of coal, peat and so on in individual countries, but these are features of modern rather than pre-modern societies and in most countries were only of marginal importance in the period concerned. There are exceptions, e.g. coal was of growing significance in the UK especially after 1600, but that reflects this country's pioneering status in the energy transition which accompanied the industrial revolution.

There are a number of striking features of this balance, which distinguish it from any modern equivalent.

- First, of course, it is made up entirely of *renewable* sources, although that does not mean that it was necessarily sustainable or environmentally benign.
- The main use of energy was for *agricultural* purposes (the animal traction entry refers to the use of horses and oxen, primarily for ploughing and hauling wagons), a minor part of the energy balance today. This reflects the structure of the economy as a whole. Output and employment in pre-modern Europe were also concentrated in agriculture, so it is not surprising that that was the major area of energy use. However, it is worth bearing this point in mind when looking forward, i.e. that energy use depends not just on the overall level of economic output, but also on its composition.

- The data in Table 1, as noted, are for *power* rather than energy (i.e. for the capacity of the system to produce energy rather than the amount actually produced). To some extent this reflects data limitations. It is possible to estimate the number of mills and horses at any one time, but much more difficult to estimate how they were used. Most of these sources are not directly analogous to modern fuels such as coal and oil (tonnes of which do represent energy). Most pre-modern sources were not available for energy production in general, only for specific uses at specific places. A mill, for instance, had a useful output only when there was something available to be milled, and because of the limits on transportation this meant only relatively local produce. Nor would the mill use up input energy when it was producing useful work, in the same way that a coal or oil-fired plant consumes energy when operating; the energy input from water or wind exists independently of whether or not there is any output.
- *Energy intensity* (that is, the amount of energy needed per unit of output) is therefore difficult to calculate. However, and perhaps surprisingly, the economy seems to have been fairly energy intensive. The figures given above suggest that Europe consumed around 15 GW of power in pre-modern times. When scaled up for population and GDP growth, this is arguably as much or more than the present requirement (see the following section). A recent analysis concludes "If we incorporate into our analysis all forms of energy use, including wood-burning, it is very probable that the energy intensity of Shakespearean England, measured in terms of joules per unit of GDP was higher than that of the UK today" (Tooze and Ward, 2005).
- One major reason for the previous point is that *efficiencies*, although also difficult to calculate, were low. Wood burning was an inefficient way of converting energy with the technology then available, and the process may indeed have got less, rather than more, efficient during the middle ages. Open fires in the centre of rooms, despite their inconvenience and health risks, probably heated living space more efficiently than the chimneys which came into use from about the fifteenth century onwards (Smil, 1994; Fouquet and Pearson, 2005). Wind and water mills were similarly low in efficiency compared with their modern equivalents and would have operated at what we would call a low load factor, for the reasons given above. With animal traction the calculation of efficiency is even more problematic – a horse or ox requires fuel input (oats, hay) whether it is working or not. However, the horse usually requires dedicated feedstuff, such as oats, while an ox can generally subsist on by-products such as straw. Energy efficiency is therefore a rather dubious calculation. Smil (1994), however, estimates the efficiency of a horse (i.e. the ratio of energy output to energy input) across a working day at about 13 percent which is relatively low, certainly compared to modern engines. Furthermore, account needs to be taken of the times when the horse was not working. At such times, it would still consume about half to two-thirds as much fuel in the form of food as during working periods, lowering its overall energy efficiency. (Of course, it might still produce some useful output, such as manure for fertiliser).
- Most of the sources listed above still exist today but are not incorporated into our energy balances. Wood burning, for instance, may well be a growing energy source, but in most cases it is not included in official energy data as wood is generally collected and traded in relatively small amounts and at a local level. Similarly, while animals are now rarely used for traction, there are estimated to be 600,000 to a million horses in England and Wales today (DEFRA, 2005), and some 2.5 million people who ride – probably more than in pre-modern England. The energy produced by these horses is not measured in a modern energy balance. It may well be regarded as of no economic relevance, since this is mainly a leisure pursuit. However, leisure use of modern energy forms, such as oil used in motor racing or air transport, is included in

national energy balances. As with the failure to accommodate most biomass use, this therefore constitutes something of an anomaly.

### *3.2 Global and national differences*

It is also necessary to stress that while the figures are given on an aggregate basis (for Europe as a whole), they should not be taken as a picture of the pre-modern world in general and do not imply uniformity across the European region. Europe was not uniform and probably not typical (data for other regions are even scarcer than for Europe so the statement cannot be quantified, but this seems to be confirmed by many sources).

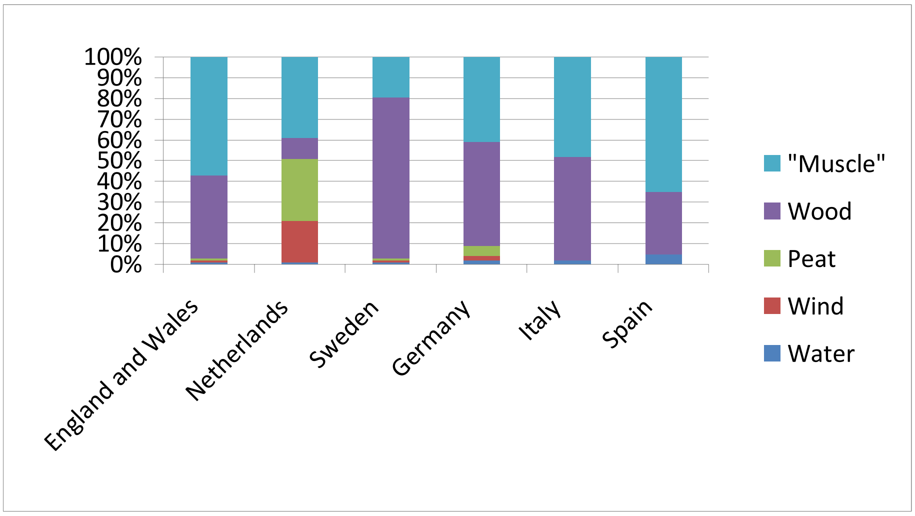
Europe was probably exceptional in being relatively energy intensive. This reflected a number of factors.

- *Climate*: Europe, in particular northern Europe, is relatively cold. Consequently, high heating needs were met by the significant consumption of firewood.
- *Agriculture*: Europe had relatively heavy soils (requiring ploughing) and tended to rely on extensive forms of agriculture compared to other regions (with the Low Countries as a partial exception; see below). Many other areas, such as India, China and Mesoamerica, had much more intensive agricultural systems based mainly on human labour. They could rely on two or even three crops a year, so required relatively less land.
- *Availability of draught animals*: Europe was also exceptional in its heavy reliance on horses. In some other areas (e.g. the Americas) draught animals were not generally available. In others (e.g. India and China), horses were expensive and tended to be reserved for military or high-status use. Horses require relatively high-energy inputs, but also have high-energy output, and took an increasing place in European agriculture from the early Middle Ages on (Smil, 1994). In other regions, manpower was often employed where Europe would have used horses, e.g. in operating mills or hauling barges (Braudel, 1981).

Europe was therefore the most energy-intensive part of the pre-modern world; this is no doubt one reason why it was the location for the industrial revolution.

However, as noted, Europe was also not uniform. Chart 1 (Warde and Lindmark, 2006) shows estimates of the energy balance in different European countries before the industrial revolution. Note that these figures are not directly comparable with those in Table 1 above. This is a sample of countries only (excluding France, the biggest economy of pre-modern Europe) and in general the dates chosen by the authors are rather late, mainly in the nineteenth century, apart from the figures for England and Wales, which represent 1560. (For specific dates, see Table 2). Nonetheless the analysis is consistent with the broad picture above and informative about regional variations.

**Chart 1. Energy balance in different countries in pre-modern Europe**



It will be seen that in northern European countries such as Sweden, wood predominated as an energy source due to the high heating needs. In southern Europe, for example Spain, muscle (i.e. human and animal power) was of greater significance. The Netherlands stands out as having a more diverse energy system (at least in 1800) with considerable use of wind power and peat. It was also exceptional in having a much more intensive farming system. However, the broad overall picture remains that of extensive use of animal and human power and almost complete reliance on renewable resources, with energy used predominantly in the form of muscle for agriculture or wood for heating.

### *3.3 Energy economics in pre-modern Europe*

Given the data limitations, there is little that can be said with certainty about the economics of energy. Braudel (1981) has explained the pattern of energy use discussed above as essentially the result of European economics (which may, as noted, have been somewhat different from the rest of the world). He puts the output of human labour (around 0.05 hp) at around one tenth that of one horse (0.5 hp),[6] while the cost of human labour at 8 sols[7] a day was about half that of a horse (equivalent to 16 sols a day). Therefore, in economic terms a horse would be preferred for tasks that required simple power (muscle) while a human labourer would be preferred for tasks that required some skill and intelligence.

For heating there were then few alternatives to firewood (apart from the very small amounts of coal and peat being exploited in the pre-modern era) so the question was generally one of affordability or availability. The choice was either to pay up, find the wood yourself, or go without.

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[6] One horse power is reckoned to be more than a typical horse could produce, at least over an extended period. The measure was defined by James Watt of steam engine fame and appears to be an unusual example of advertising non-hype. It is thought that Watt did not want to disappoint his customers and so produced very conservative figures for the power of his engines.

[7] One sol (or sou – the name derives from the Latin solidus) is an old French coin equivalent to an English shilling.

This lack of diversity had its impact on energy *prices*. In discussing “the medieval price revolution” for instance, Fischer (1996) comments:

> “Not all prices increased at the same rate. The most rapid rises appeared in the price of energy, food shelter and raw materials – items most heavily in demand during a period of population growth, and least elastic in their supply. Specially striking was the price of energy…. The cause was not hard to find. During the late twelfth and thirteenth centuries, Europe rapidly cut down its forests, consumed its timber, and burned its brushwood for fuel.”

He identifies a similar pattern in later inflationary periods, where energy and food prices tended to rise fastest. In the late eighteenth century in France, for instance,

> “…the most rapid movements occurred in the price of energy and food. The largest increase occurred in the cost of firewood and charcoal.”

### *3.4 Environmental impacts*

It will be apparent from the above that near total reliance on renewable energy forms did not insulate pre-modern Europeans from energy price volatility. Nor did it mean that the energy systems were environmentally benign and sustainable. They required very large areas of land for feeding animals and providing wood for heating. One estimate is that typical areas of Europe needed about 2 hectares per person to meet their energy needs within a traditional economy, as shown in Table 2.

**Table 2. Per capita land requirements (hectares) for energy production**

| | Humans | Animals | Wood |
|---|---|---|---|
| England 1560 | 0.58 | 0.80 | 0.32 |
| Netherlands 1800 | 0.27 | 0.13 | 0.13 |
| Sweden 1800 | 0.50 | 0.61 | 1.67 |
| Germany 1800 | 0.50 | 0.74 | 0.67 |
| Italy 1861 | 0.63 | 0.57 | 0.82 |
| Spain 1850 | 0.62 | 0.87 | 0.34 |

Source: Warde and Lindmark, 2006

The picture varies between countries, but in most cases much more land was required to support energy provision than to support humans. Although the productivity of land was (slowly) increasing, this set a limit to the size of the population. Indeed, Warde and Lindmark (2006) estimated that

> “at the yield level of the late sixteenth century, England could not have supported more than 5.3 million people with the given structure of energy demand – a figure surprisingly close to the early modern population ceiling. In other words, economic expansion that required increasing per capita energy consumption required a shift towards the greater employment of fossil fuels from an early date to be sustainable.”

Braudel (1981) reaches a similar conclusion, stating that “lack of energy was the major handicap of *ancien regime* economies”. He identifies the problem as being not so much the actual capacity to produce energy but rather that of “easily mobilised – and that means easily transportable – energy”. The pre-modern energy system was not capable of supporting economic development until fossil fuels (easily mobilised and easily transportable) changed the situation.

It is also doubtful whether pre-modern Europe had a low carbon economy (at least in terms of the intensity of carbon per unit of output or per head; *absolute* emissions were of course low by modern standards). Again, the figures are almost impossible to calculate, but the appetite for firewood led to extensive deforestation during periods of population growth. Europe followed a broad trend of forest loss up until the industrial revolution with some expansion of forest cover more recently, and the likelihood is that the two trends are connected. That is, the deployment of fossil fuels and increase in agricultural productivity are among the factors which have enabled Europe to restore its forest cover.

In addition to the direct use of firewood, the requirements for grazing and fodder crops for draught animals (as noted above, much greater than those for humans) were met by clearing land, also contributing to deforestation, while ploughing and tilling released carbon from the soil. The renewables-based energy economy was therefore not a low carbon system. The issue, like that of sustainability, is more complex than it might appear at first sight.

### *3.5 Summary: The pre-modern European energy system*

The pre-modern energy system of Europe, while fundamentally different from today’s, also presents remarkable similarities. On the one hand:

- it was almost entirely renewables based; today’s energy system is mainly fossil fuel based;
- it was based on sources which would not even enter into an energy balance today and did not have most of the sources that are used today; and
- energy use was mainly for agricultural purposes, a very minor component of today’s energy balance.

On the other hand:

- while modern concepts like energy efficiency and intensity are difficult to apply, energy use was generally at low levels of efficiency and the economy was probably fairly high in energy and carbon intensity; and
- despite the great differences in structure, many of today’s energy sector issues such as sustainability, price volatility and lack of diversity were also features of the pre-modern energy system.

## 4. ENERGY TRENDS SINCE THE INDUSTRIAL REVOLUTION

The broad trends in energy supply and consumption since the industrial revolution are well known. With industrialisation came rapid population growth and expansion of output, accompanied (or enabled) by rapid growth in ‘modern’ forms of energy. These include coal during the nineteenth century, then oil (particularly for transport use) during the twentieth century, then in the second half of the last century a range of new sources such as natural gas, nuclear and new developments in renewables.

Less well known, perhaps, is the fact that this growth in modern energy forms was not directly at the expense of traditional sources. As Table 3 shows, rapid population growth was accompanied by a steady expansion of traditional sources such as biomass, as well as of new energy sources.

Modern energy sources showed the fastest growth, of course, increasing to some 700 times their original level during the period since 1820. However, biomass also grew, albeit much more slowly (by around five times). In fact, biomass use per person remained roughly constant over the period at around 0.2 tonnes of oil equivalent (toe) per capita. Biomass is still a reasonably important contributor to the world energy balance (over 10 percent) and if other sources (such as animal and human traction) were included, the contribution of traditional energy would be even more significant. Broadly speaking, what occurred has not been the substitution of new forms of energy for old, but rather the rapid development of *new* energy-using activities, for which *new* forms of energy have been used.

**Table 3. Energy supply since the industrial revolution**

| Year | Modern | Biomass | Total | Population | Toe/capita |
|---|---|---|---|---|---|
| 1820 | 13 | 208 | 221 | 1,041 | 0.21 |
| 1870 | 134 | 254 | 388 | 1,270 | 0.31 |
| 1913 | 735 | 358 | 1,093 | 1,791 | 0.61 |
| 1950 | 1,625 | 505 | 2,130 | 2,524 | 0.84 |
| 1973 | 5,369 | 674 | 6,043 | 3,913 | 1.54 |
| 2003 | 9,579 | 1,114 | 10,723 | 6,279 | 1.71 |

Source: Maddison, 2007

One particular new form of energy, of course, is electricity. It is not shown directly in the tables above, which are concerned with primary fuels. Furthermore, electricity cannot be displayed on such long timescales as fuels such as coal. Even in countries, such as the UK and USA, which industrialised earliest, electricity was not of any significance before the twentieth century and it only became a significant part of the energy balance in many developing countries after 1950.

However, the pattern of electricity consumption growth, shown in Table 4 for the USA, tends to follow a similar pattern in every country, although of course with different starting points (Smil, 1994, Chapter 5). It consistently grows faster than other energy sources. In other words, electricity’s share of energy consumption increases everywhere once it takes off, and goes on doing so.

Modern forms of energy have therefore increased faster than traditional forms and the most modern – electricity – has increased fastest of all.

**Table 4. Growth in electricity and overall energy consumption in the USA since 1900 (per cent per annum)**

| Period | Electricity | Energy |
|---|---|---|
| 1902–1912 | 15.5 | 6.1 |
| 1912–1920 | 10.8 | 2.9 |
| 1920–1930 | 7.3 | 1.2 |
| 1930–1940 | 4.6 | 0.7 |
| 1940–1950 | 7.9 | 3.5 |
| 1950–1960 | 8.1 | 2.8 |
| 1960–1973 | 6.7 | 4.1 |
| 1973–2002 | 2.6 | 0.9 |

Source: Pre-1970: Edison Electric Institute, 1970; post-1970: EIA, 2006

### *4.1 Drivers of energy demand*

What has driven the increase in energy use? Population growth (around 6 times) has of course been one major driver in the period since 1820. However, it is by no means the sole factor. Increased energy use per capita (by a factor of 8) has been even more significant. The combination of these two factors has meant a rapid rise in *total* energy use: c. 50 times higher since 1820. This is very much less than the 700-fold increase in *modern* energy forms (those which appear in most statistics), indicating that to focus solely on modern energy will give a misleading picture.

The main reason for increased energy use per head is that output and overall consumption have increased steadily over the period since the industrial revolution. However, the relationship between output and energy consumption (that is, the trend of energy intensity, measured in terms of energy consumption per unit of output) has followed a more complex pattern. The broad impact of industrial development is to lead to an initial period of increasing energy intensity as energy consuming manufacturing industries develop, followed by a flattening off or decline in energy intensity as economies mature and an increasing share of output is made up of services of various sorts, which are normally less energy intensive.

The process has been described (Smil, 1994) as follows:

> “The growth of absolute energy consumption with higher levels of economic development hides an important relative decline. Maturing economies tend to have lower energy intensity….The British peak came around 1850, and the US economy had its highest energy intensity around 1920. Japanese energy intensity peaked only in 1970.”

See also Schurr and Netschert (1960) and Kander and Lindmark (2004).

The overall figures also conceal different trends in different energy-using sectors, summed up in one recent study (Judson *et al.*, 1999) as follows:

> “There is general evidence that income elasticities [of energy demand] decline with income, particularly at the highest income levels. The negative top-segment elasticity …appears to be driven entirely by the *Households and other* sector. As per capita

> income rises, our estimates imply that this sector's share of aggregate energy consumption tends to fall, while the share of *Transportation* tends to rise, and the share of *Industry and Construction* follows an inverse-U pattern."

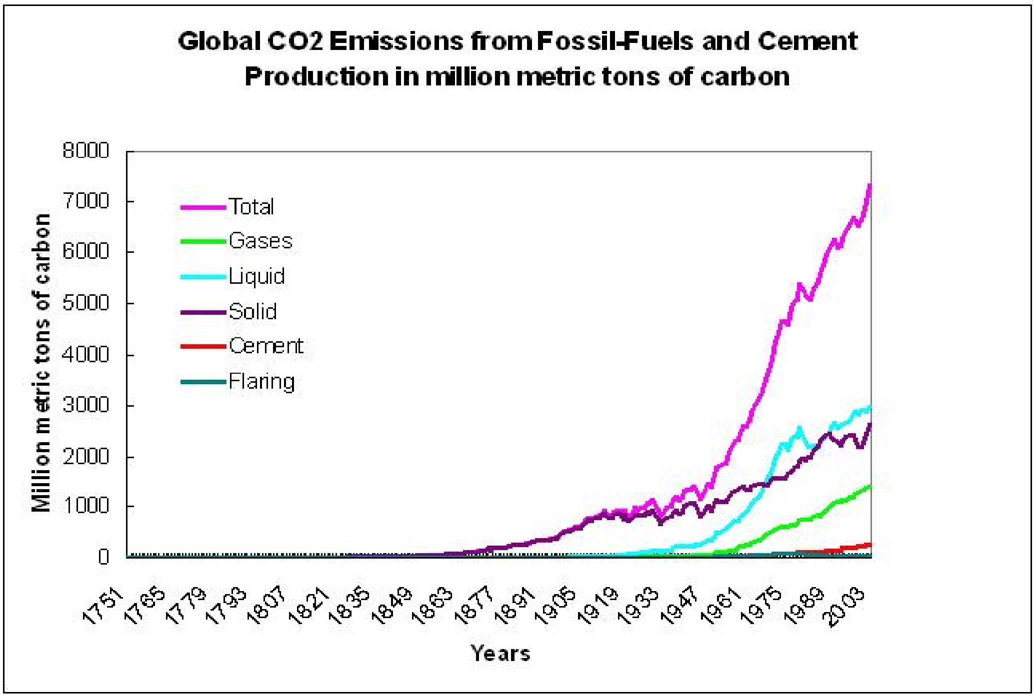
In fact, the development of energy intensity over time reflects a number of factors, not all of which pull in the same direction.

- *Economic structure*: In the early stages of industrialisation, the industry sector grows rapidly as a proportion of GDP (and agriculture declines); energy demand therefore grows rapidly. In the later stages (probably better described as post-industrialisation), industry declines as a proportion of GDP and the services sector grows. This tends to reduce the rate of growth of energy demand.
- *Industrial structure*: Even within the industry sector, a change tends to take place as economies mature (and wealth increases) from more materials-intensive to more knowledge-intensive output.
- *Demand saturation*: It is possible in principle that there is a natural limit to some energy demand (i.e. that people only need so much heating and lighting and can only drive so far in a year) and that once this is satisfied demand will stabilise. A factor such as this may underlie the declining income elasticity of the household sector noted above. However, there is no strong evidence to suggest that we are ever likely to reach a natural limit to overall energy demand.
- *Economic maturity versus technical progress*: Technical progress tends to increase efficiency, including energy efficiency, and reduce per unit energy consumption. Energy projections often include an element known as 'autonomous energy efficiency improvement' for this reason, which tends to run at a little over 1 percent a year. When economies are growing rapidly and industrialising fast, this element is not usually pronounced enough to offset the underlying increase in demand (although there is in principle scope for developing countries to increase the rate of energy efficiency improvement more rapidly by 'leapfrogging', i.e. adopting the latest and most efficient technologies from developed countries). However, there is a clear tendency for the rate of economic growth to slow down as economies grow beyond a certain point. If the underlying rate of technical progress remains roughly constant at around 1% per annum, it can have a significant effect in offsetting the increase in demand arising from the rate of growth of output where that is relatively low (say 2–3 percent), slowing down or even eliminating growth in energy demand.
- *Demographics*: A general feature of industrialising economies is that in the early stages they experience a population explosion, followed by a slowing of population growth or even stabilisation, as incomes increase. The result is that demographic characteristics change: the population gets older. In general, this tends to lead to a decline in per capita energy consumption, as older people tend to spend more time at home and in relatively low intensity activities. They spend less on transportation and car use and more on health and other services than the population in general. One recent study of the USA suggested that on a low population growth scenario (or aging population), $CO_2$ emissions would be nearly 40 percent lower than in a reference case, primarily because of the lower energy demand (Dalton *et al.*, 2005). It is suggested that the effects of aging can be as large as, or even larger than, the effects of technical change. This is not of course simply a US phenomenon. Worldwide, the rate of population growth is slowing and populations are aging. Many developing countries are likely to be affected, particularly China because of its one child policy

### *4.2 Trends in $CO_2$ emissions since the industrial revolution*

The main component in the growth of modern energy forms has been the increasing use of fossil fuels, and this has major implications for sustainability and particularly for $CO_2$ emissions. Chart 2 depicts the enormous growth in emissions associated with the increase in fossil fuel use.

**Chart 2. Global $CO_2$ emissions since the industrial revolution**

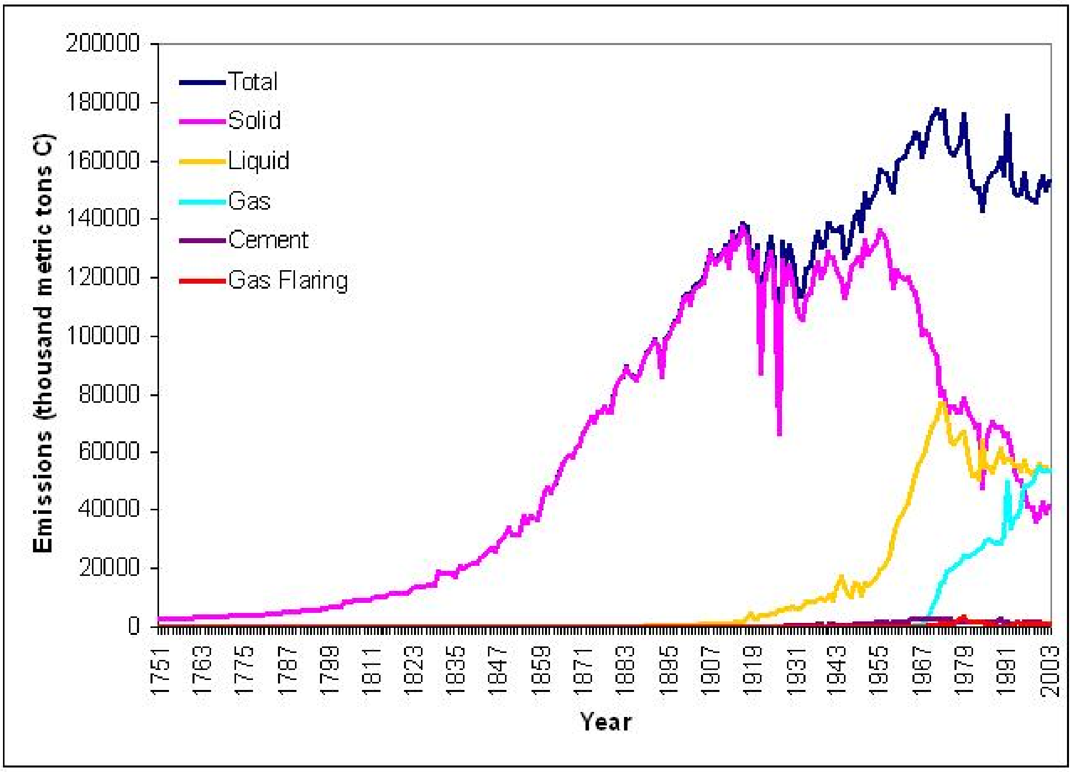


Source: Carbon Dioxide Information Analysis Center (CDIAC)

As Chart 2 shows, emissions from fossil fuel combustion grew steadily in the nineteenth century from a very low base in the previous one. This rise was mainly attributed to the burning of coal. Emissions increased at a greater rate in the twentieth century as oil use, and a little later natural gas use, took off. (Note that the chart shows fossil fuel emissions only. Emissions associated with traditional energy forms, e.g. as a result of deforestation, are not included, so the total impact of anthropogenic energy consumption is not depicted.)

The UK was the first country to be affected by the industrial revolution and one of the first to emerge into the post-industrial era. The UK-only figures depicted in Chart 3 may be of wider significance.

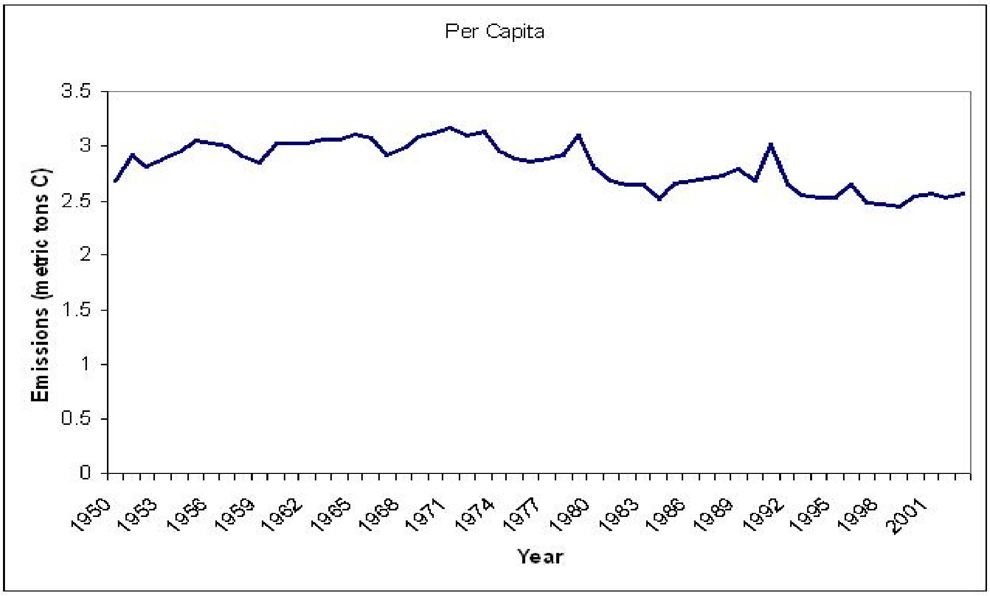
### Chart 3. UK $CO_2$ emissions since the industrial revolution



Source: CDIAC

As Chart 3 shows, $CO_2$ emissions from the UK have broadly stabilised since the 1950s. This reflects a stabilisation, or even a slight decline, in per capita emissions.

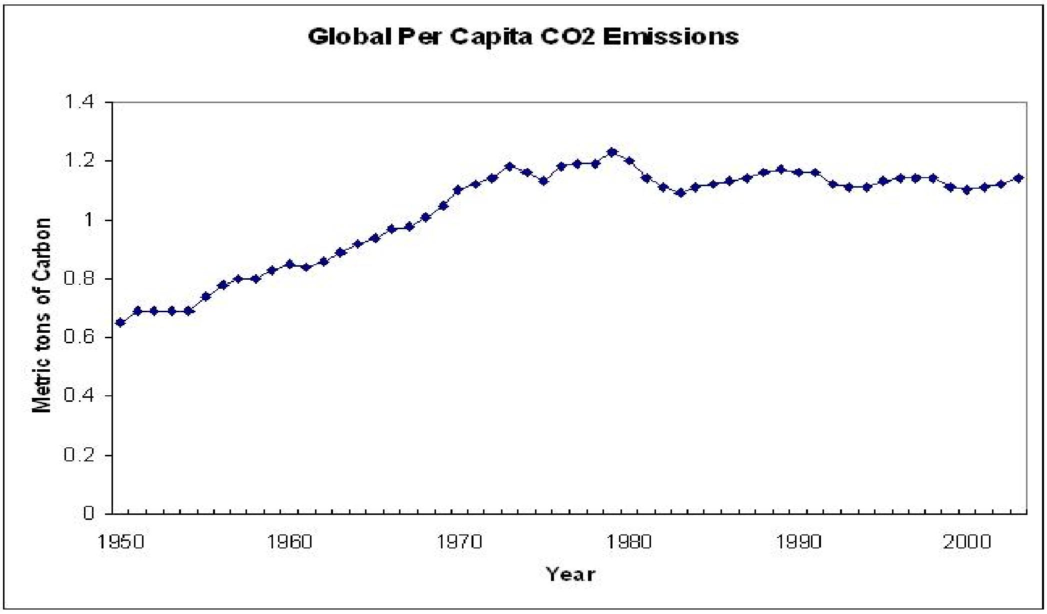
### Chart 4. UK per capita emissions of $CO_2$ since 1950



Source: CDIAC

Chart 4 depicts per capita UK emissions since 1950. This same pattern, starting a bit later, can be observed globally; per capita emissions globally have been approximately stable since around 1970, as depicted in Chart 5.

**Chart 5. Global per capita $CO_2$ emissions since 1950**



Source: CDIAC

Since economic growth has continued, this implies that the carbon intensity of GDP has been declining. The figures listed in Table 5, extracted from a different source (Maddison, 2007), show a similar pattern: $CO_2$ intensity of GDP peaked in around 1913 along with energy intensity, and $CO_2$ emissions per head globally have been stable or declining since 1973.

**Table 5. Global $CO_2$ emissions intensity since 1820**

| | Per $000 GDP | Per head |
|---|---|---|
| 1820 | 0.020 | 0.01 |
| 1870 | 0.132 | 0.12 |
| 1913 | 0.345 | 0.53 |
| 1950 | 0.306 | 0.65 |
| 1973 | 0.289 | 1.18 |
| 2003 | 0.169 | 1.09 |

Source: Maddison (2007)

Another study has reached a very similar conclusion, namely that the carbon intensity of output in the Organisation for Economic Cooperation and Development (OECD) has been “on a downward trend since 1920 and is now below the starting point in 1870” (Tooze and Warde, 2005). The broad picture of declining carbon intensities can therefore be regarded as fairly robust.

## 5. ISSUES AND QUESTIONS

One major question arising from the previous section regards the significance of the decline in carbon intensities. Is it simply a matter of chance or is there some underlying inevitability about the trend? If so, this might simplify the global task of reducing emissions. The current rise in emissions may be a blip due to the rapid industrialisation of developing countries, which may in time settle down to a much less carbon intensive future without the need for any major policy interventions.

The suggestion that the rate of emissions growth tends to slow down above a certain level of development is known as the *carbon Kuznets hypothesis*; see the box below**.** Formally speaking, it postulates that the rate of growth of emissions (or even the absolute level of emissions) might follow an inverted U-curve in the same way as the rate of growth of industrial production.

### The Kuznets hypotheses

The *Kuznets hypothesis* relates to income inequality. It suggests that inequality increases during the early stages of economic development but after a certain point declines.

The *environmental Kuznets hypothesis* applies a similar framework to environmental damage; it suggests that it first increases then decreases with rising income.

The *carbon Kuznets hypothesis* takes the principle into the specific area of carbon dioxide emissions. It postulates that the rate of emissions growth will follow a roughly U-shaped curve. That is, emissions will grow slowly in economies below a certain level of GDP, then increase rapidly once a threshold is passed, then flatten off again, or even decline, as economies reach a given level of wealth.

The overall carbon intensity of an economy can be decomposed into two factors: energy intensity, as defined above, and the carbon intensity of energy (i.e. how many grams of $CO_2$ are emitted per joule of energy used).

Regarding the former, we have already noted a trend in declining energy intensity as economies mature. This does not necessarily translate into an absolute decline in energy consumption. However, if the carbon intensity of energy declines at the same time, this may well lead to an absolute decline in carbon emissions. Indeed, this has occurred on a number of occasions, particularly in Europe, as a result of changes in the structure of the electricity system (e.g. France 1979–1989; Sweden 1979–1983; the UK 1990–1995).

In addition to the strong tendency to lower energy intensities as economies mature, some factors can also be identified as tending to lead to decreased carbon intensity.

- *Structural shifts*: The structural shifts in energy demand noted above tend to lead to reduced carbon intensity after a certain stage of development. Industry in newly industrialising countries tends to use relatively carbon-intensive fuels, usually coal and heavy fuel oil, because they are the cheapest. In other sectors these fuels might be impractical or less desirable because cleanliness and convenience are more highly valued. Those sectors tend to use fuels which are less carbon intensive. As industry's share of GDP declines over time, carbon intensity therefore also tends to decline.

- *Energy supply*: Allied to this is a change in the energy supply structure. As economies develop, the share of the energy mix taken by 'network' industries (natural gas and electricity) tends to increase. These forms of energy tend to be relatively expensive per unit and require the construction of capital intensive infrastructure. They therefore tend not to be widely available in the first stages of industrialisation. Developed countries are much more dependent on electricity and gas, at least outside transport. For instance, in the UK, over a relatively short time scale (since 1970) the share of energy demand taken by the network industries has more than doubled (from 21–52 percent) with the bulk of the rest being oil in transport. As the earlier charts indicated, this reflects a wider global trend. The share of natural gas in the energy balance has increased in many countries and is expected to carry on doing so while the share of electricity is increasing everywhere. The implications are considered below.
- *Policy intervention*: Richer countries can often afford to adopt stronger policies with regard to reducing emissions and invest in more expensive or capital-intensive sources (nuclear, renewables, for example). They can also afford to remove energy subsidies and/or tax energy sources because the social impacts on their populations are less than in developing countries, and easier to offset. This generally works to reduce both energy intensity and carbon intensity, as energy taxes often (but not in all cases) aim to encourage less polluting fuels. In general, very few subsidies for energy remain in OECD countries and many energy sources are highly taxed. In non-OECD countries, by contrast, subsidies and cross-subsidies are common. Over time, these countries can be expected to become more similar to the OECD in this respect.

Nonetheless, although there are factors which may promote the relationship implied by the carbon Kuznets hypothesis, it does not stand up to statistical analysis (Müller-Fürstenberger *et al*., 2004). This seems to be because there are a number of complicating factors, including the following.

- *Resource endowment*: The energy use of individual countries reflects, among other things, their resource endowment. Consumers in those countries with large energy resources, particularly resources with high transport costs (such as coal and natural gas) often enjoy them at a lower price than consumers on the world market. In most cases, they avoid international transport costs, which can be considerable. For example, in the case of coal and gas imported to Europe, the total cost of transportation (including carriage within the country of origin, transportation or transmission from the country of origin to Europe and delivery to the final consumer in Europe) can be well over half of the final cost of the fuel. In addition, in some cases, countries subsidise domestic use of indigenous fuels or charge a lower price than for exports, as a way of helping their citizens to benefit directly from the country's own resources. Countries therefore tend to consume relatively more of the resources which they possess in abundance. For instance, the two most populous and fastest-growing developing countries in the world today – China and India – rely very extensively on indigenous coal, not just for industrial use but also for electricity generation. Even if their economies move towards more dependence on services, they may not see such a big change in their energy supply structure as has been experienced in countries like the UK. They may continue to use less natural gas than developed countries and the carbon intensity of their electricity, mainly produced from coal, may remain high.

- *Technology*: The technology available at similar stages of development in different countries will depend, of course, on when they reach that stage of development. In some cases this will permit ‘leapfrogging’ to lower carbon processes, as discussed above. But sometimes it will mean the reverse: ‘leapfrogging’ to carbon intensive activities that were less prevalent in developed countries when they were at a similar stage of development. For instance, a much more rapid growth of car use has taken place in many newly industrialised developing countries than happened in the OECD; electrification has also tended to be faster. Since there are as yet few alternatives to oil in transportation, and since electricity generation is often a carbon-intensive process, this may also lead to increased emissions.
- *Growth of upstream energy*: Energy analysis often focuses on final demand sectors (i.e. the use of energy by industrial, commercial, domestic and other consumers). But the energy industry itself is a major user of energy. Resource extraction is one major area of consumption, but the key area is energy conversion: principally oil refineries and power stations. These already account for around half of emissions, as shown in Table 6.

**Table 6. Sectoral shares of $CO_2$ emissions**

| Sector | 2003 emissions $CO_2$ (Gigatonnes) | Share (%) |
|---|---|---|
| Electricity | 9.9 | 41 |
| Fuel conversion | 1.7 | 7 |
| Industry | 4.5 | 18 |
| Transport | 5.1 | 21 |
| Buildings | 3.2 | 13 |

Source: IEA (2006)

Furthermore, this proportion is set to increase. Electricity is expected to continue increasing its share of the energy market. The transportation of coal is likely to increase as world coal trade develops. Natural gas is likely to be transported over longer distances (and increasingly in liquefied form) as indigenous supplies decline in many regions, such as Western Europe and the USA. The production of oil is likely to become more energy intensive as heavy oil and oil sands increase in importance; processing these sources to extract useful oil is itself very energy intensive. In the medium term, the development of such techniques as coal-to-liquids and gas-to-liquids will increase energy requirements even more substantially. In the longer term, developments such as the greater use of hybrid and electric vehicles or the use of hydrogen fuel cell vehicles could result in an even higher proportion of transport emissions being shifted upstream. As a result of developments such as these, the IEA forecasts that by 2050 nearly 60 percent of $CO_2$ emissions will come from these upstream sources (IEA, 2006).

The carbon intensity of future economies will therefore depend not just on what happens to consumer demand for energy, but on how that demand is met, and while there are factors which may reduce intensities, there also significant factors which may tend to increase them. In short, while there seems to be no inevitability about increased carbon emissions with increased growth and energy demand, there is on the other hand no inevitability about declining carbon intensities either. The position will differ in different countries at different times and significant policy intervention is likely to be needed in many cases to secure an environmentally acceptable result.

### *5.1 The nature of future energy demand*

If the picture in relation to carbon intensity gives no room for complacency, but equally no reason for undue pessimism, what about the future of energy more widely? What can we say about future energy supply and demand and the wider role energy will play in future economies?

The problem with very long-term forecasting is that the usual methodologies are not very useful. Forecasts such as those of the IEA tend to be based on some estimate of economic growth and of future energy prices; forecasts of prices in turn ideally stem from structural analysis of supply and demand and the variables that determine them. However, as one long-run study of prices has pointed out "structural models are not always useful for long-run forecasting, in part because it is difficult to forecast the explanatory variables in such models …over long horizons" (Pindyck, 1999). An alternative is to extrapolate from the current situation, making assumptions about the sort of path that energy prices might follow (say, a random walk or reversion to some trend, possibly based on assumptions about resource depletion or technological change). It has to be said that, whatever their basis, energy forecasts have not in general been very successful. As noted above, even over periods of a few decades, they have not been effective at forecasting changes in trends. Over periods of hundreds of years, variables such as technologies, economic structures and energy prices are almost impossible to project with any confidence so that any forecast tends to become simply an elaborate working out of a set of more or less arbitrary assumptions.

It might therefore be worth considering whether there are other ways in which we can think about the future of energy. As highlighted above, we do not have to go back very far (200 years) to find a world where the concept of 'energy' did not exist, and the fuels and technologies of today's world were unheard of. The same may apply to the future. Most forecasts, and indeed most energy analyses, are based on demand for particular fuels and assumptions about the technologies that will be used. However, over a long time period energy may not mean just a particular set of fuels and technologies of the sort we are familiar with today; we may be talking about completely different processes.

### *5.2 Energy services*

An alternative approach, much favoured by proponents of energy efficiency, is to think in terms of energy services. Energy is a 'derived' demand; we do not want to consume gas or electricity in their own right but for the services they provide, such as heating and lighting. If those services can be provided with lower inputs of primary energy (which is nearly always the case, as technologies and processes get more efficient) a growing society could meet its underlying energy needs without needing to consume more primary energy. In principle, not only could carbon be decoupled from energy, but energy could be decoupled from economic development.

The difficulty with this approach, as it relates to the longer term, is that it substitutes one set of problems for another. Can we forecast what energy services people will need in the distant future, and how those services will be provided? In terms of this paper, it raises the question: can the experience of the past tell us anything about energy services, as well as about fuels? This topic is even less studied than that of energy supply and demand, partly because, as discussed below, quantifying the output of energy services is even more difficult than quantifying the fuel inputs to those services.

Nonetheless, it is clear that the trend shift which occurred at the time of the industrial revolution related not only to the fuels themselves, but also to the energy services being provided. Indeed, in a way, the changes in service provision have been even more fundamental. All sources of energy are ultimately commensurate; they can all be measured in the same units because all forms of energy can be converted into heat. Energy services are more varied in nature, and have changed fundamentally since pre-modern times.

In traditional societies, as discussed above, the main energy services were “muscle”, that is, work in a physical sense, and heating. (Transport is in a sense a form of muscle too, but can be distinguished in its primary purpose – to move from A to B – whereas muscle was used to perform work in particular locations. Pre-modern societies needed a lot of muscle but did not consume a great quantity of transport services in the modern sense of moving between places.)

Table 7 displays a valiant attempt to measure long-term trends in consumption of certain energy services.

**Table 7. Consumption of energy services in the UK since 1700**

| | 1700 | 1800 | 1900 | 1950 | 2000 |
|---|---|---|---|---|---|
| Power (TWh) | 0.4 | 1 | 20 | 28 | 120 |
| Transport (Bn p/km) | 0.6 | 1.9 | 29 | 190 | 735 |
| Lighting (Trillion lumen hours) | 0.005 | 0.05 | 11 | 250 | 1,270 |

Source: Fouquet and Pearson (2005)

1. Power, measured in Terawatt hours, does not of course represent solely electricity; it includes the physical work of moving objects, powering mills and machinery, etc.
2. Transport refers solely to passenger transport, measured in billions of passenger kilometres.
3. Lighting is measured in output terms: trillion lumen hours.

These figures represent the total consumption of energy services across the economy. Of course, population has also risen over the period since the industrial revolution, but even on a per capita basis, there has been an enormous increase in the consumption of energy services. It has been estimated by Fouquet and Pearson (2005) that since 1750, each person uses on average:

- 50 times more power;
- 250 times more passenger kilometres; and
- 40,000 times more lighting.

It may also be worth adding that according to the same authors this has happened along with an equally enormous increase in energy efficiency in the provision of these services, of the order:

- 100 times for power;
- 20,000 times for transport; and
- 1,000 times for lighting.

These efficiency figures are, of course, very difficult to calculate with any precision. In particular, the data for transport take as their starting point a calculation of the efficiency of a horse at converting oats into passenger kilometres; it is not clear how useful a calculation this is, as discussed above. Nonetheless, the broad trend seems strongly established that, in the words of the authors of these estimates, “from the beginning of the nineteenth century, the average efficiency for a particular service always improves”.

As this indicates, there is no simple relationship between energy efficiency and energy demand. The explosive growth in energy demand since the beginning of the nineteenth century has been associated with a steady growth in efficiency. This is not in itself surprising; greater efficiency in providing a service normally lowers the cost of that service, so stimulating demand for it. For instance, the IEA (2006) estimates that the real cost to the consumer of providing lighting has fallen to one-six-thousandth of its level in the sixteenth century. Whether faster consumption of an energy service means greater consumption of input energy will depend on the relative rates of increase. However, the balance is complex, and it is certainly not the case that energy efficiency leads automatically to lower energy consumption.

In the example above, lighting was only consumed in very small quantities before the industrial revolution. Lighting (via tallow candles from animal fat) was expensive, inefficient and inconvenient. Most households, apart from the very rich, tended to do without, using minimal lighting (e.g. the by-product of wood-burning for heating purposes) or none at all. It is to a large extent the greater efficiency of lighting (and the consequent collapse in the cost of providing it) which has led to its development into a significant energy use, accounting for nearly 19 percent of electricity production globally, according to the IEA (2006).

Similar trends might be identified in other uses, such as cooling. Before the industrial revolution this would almost certainly not have been thought of as an energy service. Cooling was effected by house (and garden) design, by changes in activity levels (e.g. sleeping under a tree in the middle of the day) and only at the margin, or in hot countries, by the use of fans and other cooling devices. It was when the efficiency of air-conditioning technology increased in the twentieth century that cooling became a firmly established energy use, to the extent that in many parts of the world (including the USA) it is now the largest single use of electricity.

Quite apart from these now mainstream energy services, there is a huge range of new applications particularly in various forms of electronics, information technology and telephony which would have meant little or nothing to an inhabitant of pre-modern Europe. According to the EIA, some 40 percent of US household electricity demand is accounted for by a huge range of miscellaneous appliances (i.e. those other than the mainstream uses of heating, cooling, lighting and refrigeration and including such items as dryers, computers, answering machines).

In other words, although there has been a huge growth in the consumption of energy services, what is most striking is not the growth in *traditional* energy services but in services which were once marginal or non-existent. Even where the services were known to pre-modern economies, in many cases the growth rate is so staggering that it amounts in effect to a change in the nature of the service being provided. While the concept of lighting would have been comprehensible to a pre-modern European, it is doubtful whether he or she could have grasped how anyone would need, or be able, to consume 40,000 times as much of the service as they did. It was simply incommensurate with their experience and understanding of the technological options available. Translating the service figure into familiar terms – 40,000 tallow candles smoking and spluttering throughout the house – would have conjured up an absurdly impractical scenario which they would have rejected out of hand. And, of course, charging up a battery for an iPod or mobile telephone would have been completely meaningless.

The important message is, when considering the future role of energy in providing services, not to judge solely from our own experience of what constitutes an energy service. Indeed, it is probably unhelpful to think about energy in terms of those services currently being provided. There is a risk that in doing so, we limit our conception of the future by what we find graspable.

### *5.3 Trends in energy service demand*

What do the long-term trends described above tell us about the nature of energy demand? First, there is a trend which might be called *dematerialisation*, both of energy sources and of energy services. In a general way, this parallels dematerialisation of the economy more widely: the move from manufacture of physical goods to an economy which is both service and information intensive. Energy sources have themselves become both less physical and less local. Pre-modern sources were generally physically accessible, familiar and comprehensible, e.g. wood from local forests; draught animals on farms; the wind and water, whose force everyone would recognise from direct experience.

One key problem, however, was that this energy was not transportable or particularly convenient to use. The need for transportable power led to a shift to forms which were more concentrated, both in terms of heat (the energy density of wood is about half that of coal and that of coal not much more than half that of oil, depending on the grade; Smil, 1994, Chapter 1) and in geographical terms (i.e. the amount extractable from a given area), making them more transportable. Growing incomes and new technologies led increasingly to the need for forms of energy which were more convenient and easily used. Oil can be readily transported, pumped and stored for use in personal transport. Coal-driven steam cars, although technologically viable, cannot compete for convenience of use. The services being provided by energy even at a fairly early stage of the industrial revolution were already more than just heating or motive power; they included less physical attributes such as user-friendliness.

Gas is rarely perceived as a physical product by the consumer, from whose perspective it shares many characteristics with the other network source: electricity. Effectively, it bundles up a whole package of services into a simple but intangible product. It is this premium value which means that, whatever happens to the relative prices, people rarely revert to coal from gas for domestic heating. Coal is still a physical product, from a user perspective. It has to be delivered and stored, introduced to the boiler or grate as needed, and the ashes cleared and disposed of. Gas, by contrast, is both physically and metaphorically invisible. The consumer does not need to take any active part in the heating process: thermostats control the boiler; the gas network takes care of gas storage and balancing as well as provision on demand to the consumer; waste products are disposed of automatically.

Electricity takes dematerialisation one stage further, indeed to the extent that it becomes something of a metaphysical or legal question whether it is a good or a service, with views changing over time (Keay, 2006). Its key attribute is its flexibility: it can be used for the provision of virtually any service e.g. heating, cooling, motive power, lighting, telecommunications or information processing. Electricity is the most expensive form of energy (unsurprisingly, since it is mainly generated from other energy sources with an associated loss in efficiency). But it is also the most steadily growing and highest-value form of energy. As this combination indicates, the value of energy increasingly resides not primarily in its pure calorific or power content, but in its ability to provide a range of services flexibly and conveniently.

This sets up two conflicting tendencies as far as energy is concerned. On the one hand, as economies mature and become more service and information intensive, they generally become less energy intensive, in terms of energy consumption per unit of output. On the other hand, their demand for energy also changes to forms that are more service intensive and less material in nature. These in turn open up the possibility of new, value-added energy services, so creating new forms of demand for energy. The net effect, as the charts above indicate, is that decreasing energy intensity is not incompatible with increasing absolute energy use. Traditional forms and uses of energy may indeed decline in relative terms but new forms and uses of energy tend to increase. The net effect on energy demand (i.e. whether it goes up or down overall) depends on the circumstances. What does seem clear is that there is little reason to believe that demand for energy in general, as opposed to demand for energy for particular applications, is likely to saturate.

### *5.4 Future energy services*

As energy moves away from its traditional forms to more service-intensive forms, the ultimate functions it provides are also changing. Two in particular may be identified as likely to be of importance for future economies.

The first is *intelligence*. We do not normally think of intelligence as an energy service as such, but (like most other services) it takes energy to provide. Indeed the human brain itself consumes as much as one-sixth of our energy need, three times as much as the brain of a chimpanzee (Smil 1994). Information and communications technology in its various forms is a significant consumer of electricity, totalling about 10 percent of US household consumption according to the EIA. The information industry is itself a heavy user of power. Servers and other internet support structure alone consume the equivalent of the output from some 14.1 GW power stations worldwide, and their demand is doubling roughly every five years (Koomey, 2007).

However, information technology is currently primarily a static phenomenon, i.e. something which does not itself move like a computer, or which is carried around like a mobile phone. This could change in future. For instance, the UN Economic Commission for Europe in its 2004 World Robotics Survey forecast that by 2008, some 4 million domestic robots will be in place and that in the long run, robots will:

> “not only clean our floors, mow our lawns and guard our homes but also assist old and handicapped people with sophisticated interactive equipment, carry out surgery, inspect pipes and sites that are hazardous to people, fight fire and bombs”.

All of these robots will no doubt be powered by electricity. In many of the cases listed above, they will be carrying out tasks which we do not think of as energy-consuming. Most current energy projections do not specifically recognise such activities or other possible new energy services. The list above is by no means complete; one might add such tasks as taking the dog for a walk, picking up shopping or acting as personal trainers. In fact, the potential list is endless. What it represents is tasks that involve the application of intelligence along with the need to perform work in a physical sense. In the past, as we have seen, energy consumption generally involved the substitution of natural for human energy in tasks not requiring significant intelligence. In the future, opportunities will present themselves for substituting energy-consuming devices for humans and the scope for doing so and developing new energy services will be, in principle, unlimited.

The second major factor is *time*. Energy services increase the output possible in a given period of time, which can be seen either as an increase in output, or a saving of time. For instance, the horse whose output was ten times that of a man in pre-modern Europe could be regarded as saving the work of nine people (assuming the horse needed to be guided by a person) or as saving one person nine days of time.

When time is included in an economic calculation, as in the example quoted in Section 2 which looked at the cost of a man or a horse per day, its value can be monetised. However, when it comes to end-uses and the individual consumer, the time element of an energy service is often ignored. Take, for instance, the output figures for transport in Table 7 above. This uses the normal definition of transport output: passenger-kilometres. Yet a moment's thought makes it obvious that the service provided by transport is much more than this: it includes comfort, convenience and, above all, time. Inter-city trains compete directly with air transport only when they offer a comparable time for city centre to city centre transport. Running at half the speed, they would still provide the same number of passenger-kilometres, but not the same service as far as consumers were concerned.

This is a feature well recognised in transport cost-benefit analyses (e.g. for the construction of a new road or by-pass). In nearly all cases, the biggest single item in such analyses is the time saved by drivers and passengers from using the new facility. One estimate of the costs associated with US road transport suggests that the average time costs for US car travel are more than three times as great as running costs (and six times as much as fuel costs; Small, 1992). Similarly, contrary to what many might suppose, the largest externality associated with personal transport is not environmental (greenhouse gas and other emissions) or even the cost of accidents, but congestion: the time penalty users impose on each other. For instance, a report by the Institute for Transport Studies (Nash et al., 2004) suggests that "congestion costs dominate marginal external costs", accounting for between two-thirds and four-fifths of road user external costs, depending on the assumptions used.

This applies not just to transport but to nearly all areas of energy consumption, yet is rarely taken properly into account. One recent study of the energy efficiency rebound effect (Dimitropoulos and Sorrell, 2006) suggests that

> "perhaps the greatest area of neglect is the time costs associated with energy service provision…the substitution of energy for time in the provision of energy services, together with the parallel 'rebound effect with respect to time' are likely to be important drivers of increases in aggregate energy consumption".

It points out that time is, for consumers, an input to the production and consumption of energy services and that the efficiency of time use may be an important factor in the choice of services. For instance, a microwave oven is more time efficient than a conventional oven, an aeroplane is more time efficient over distances than a car, and consumers factor this into their calculations. The results in terms of energy efficiency may vary. In the examples given, the microwave would normally be the more energy efficient choice; the aeroplane the less energy efficient.

What is the significance of this to long-term trends? Simply that almost every economic projection – whether by the IEA, EIA or Stern – assumes that economies and incomes will grow over time. It follows that the valuation people place on time will also grow, since time can be measured in terms of income foregone. This adds an extra layer of complexity. The increasing value of time is likely to lead to the substitution of energy services for time but (as with energy efficiency and the growth of new services) the net impact on energy demand is likely to be complex.

The analysis could be taken much further, of course, but this paper does not set out to provide comprehensive answers. The object is simply to draw attention to some themes which a study of the long-term trends of the past might raise for those projecting the energy trends of the future. The main message is simple: that we have to try to distance ourselves from the particularities of today's energy systems in order to identify the more fundamental aspects of energy's role in society. When we do so, the uncertainties are much greater than they appear at first sight. There is little we can take for granted about the nature of the energy system hundreds of years into the future. Just as our energy markets today would have been inconceivable to an observer from pre-modern Europe, so we need to be cautious in conceiving the energy markets of the future.

# 6. SUMMARY AND CONCLUSIONS

## *6.1 The need for a long view*

- In a world increasingly concerned about sustainability, it is often necessary to take a long view of the nature of energy and its role in society. Projections of energy use and the associated emissions for centuries ahead are becoming important inputs into decision-making. We need to ensure we have the capacity to think about long-term trends in a robust fashion, and to get beyond the extrapolation of particular aspects of the present.
- Examination of the energy trends of the past will not enable us to forecast the future, and it entails many difficult methodological and data issues. Nonetheless, it raises important questions about the fundamental role of energy and helps us to think more carefully about what that role might be in the future. It enables us to be more critical of the assumptions we are making and more aware of the uncertainties involved.

## *6.2 The pre-modern European energy economy*

- The pre-modern European energy scene was in many ways fundamentally different from that of today. Not only was it almost entirely based on renewable sources, but the main forms of energy used then would not even enter into an energy balance today. Equally, a pre-modern European would not have recognised most of the sources that are used today – and would not even have understood our concept of ‘energy’. Energy use was mainly for agricultural purposes (a minor component of today’s energy balance) and for heating, while the major energy services familiar to us today were largely unknown. Even the concepts used in analysing energy systems, such as energy supply and demand, energy efficiency and energy intensity, are difficult to apply meaningfully.
- Despite these great differences, many of the most significant issues facing the energy sector today such as sustainability, price volatility and lack of diversity were also features of the pre-modern energy system. Energy use was in general, as far as it can be robustly estimated, quite inefficient and, despite the dependence on renewables, fairly carbon-intensive. Europe was the most energy-intensive region of the world, and energy was the main constraint on the development of pre-modern Europe. The pre-modern structure of energy supply and demand was not sustainable.
- The unsustainability of pre-modern energy production was partly due to the technical limitations of the mechanical energy then available (primarily wind and water mills) whose output could not be converted into a transportable form. This constraint has of course now been largely removed because of the availability of electricity (and potentially in the future, hydrogen) as an energy carrier.
- However, an additional constraining factor on pre-modern sources (high land use) is of more fundamental significance. The main energy sources then were animal power (horses and oxen) for traction and firewood for heating. Growing fodder for the animals and harvesting firewood from forests involved a significant use of land, perhaps twice as much as was needed for growing crops for humans. This created direct competition between fuel and food uses of land, and was associated with extensive deforestation and land clearance. Such problems persist today, as has been seen recently in relation to biofuels. This does not imply that renewables are inherently unsustainable, only that – as with other sources – we have to consider their sustainability on a case-by-case basis and in relation to the particular circumstances.

### *6.3 Trends since the industrial revolution*

- The industrial revolution saw an exponential growth in overall energy consumption and production. However, there are signs that as economies mature the rate of growth in energy demand slows down and energy intensity starts to decline. There are many reasons to expect that this will continue to be the case with developing countries today.
- Long-term trends seem to show that global energy intensity of output peaked around 1913, while energy consumption per head peaked around 1973. These downward trends are likely to continue, but will not necessarily lead to a decline in energy demand.
- The growth in overall demand is accompanied by a shift in the balance of fuel use. Traditional sources dominate pre-industrial societies. With industrialisation, however, first coal, then oil, then the network sources (electricity and gas) have tended to predominate. (Oil has, however, remained the fuel of choice for transportation, which continues to show steady growth.)
- This shift in the energy balance has not been due simply to the substitution of new forms of energy for old forms. Traditional energy sources continue to be as significant as ever and coal is currently the fastest-growing energy source. However, new energy sources have generally grown much faster than traditional forms.
- The trend towards the network industries can be expected to continue, and is reflected in most forecasts. Because networks require significant infrastructure development, they tend to be slower to take off at the early stages of industrialisation. The network sources are also more expensive than the earlier forms. This higher cost reflects higher value; the network fuels package together a range of services along with the provision of pure calories, are more attractive to higher-income consumers and more suited to a service and information-oriented economy.
- The growth of the network industries has implications for the relationship between energy consumption and $CO_2$ emissions, but these are complex. On the one hand, natural gas is a relatively low-carbon fuel and electricity can be produced from zero carbon sources; in these circumstances the increasing share of the network fuels would lead to lower emissions. However, electricity can also be generated from high-carbon sources such as coal and, because of the efficiency loss involved, this will tend to push up $CO_2$ emissions.
- Furthermore, energy conversion and upstream energy use are increasingly dominating carbon emissions. Coal is both the cheapest and most abundant of the fossil fuels. As well as producing electricity it can also in principle (and sometimes in practice) be used to manufacture gas or liquid fuels (and potentially hydrogen). Without countervailing policy action (e.g. to require carbon capture and storage) the growth in energy conversion could lead to increased emissions.
- This illustrates the complexity of the relationships involved. It is not just the level or even the structure of final energy demand which will drive $CO_2$ emissions, but the structure of primary energy supply and of the conversion sector, which is likely to be the main source of future $CO_2$ emissions.
- Global $CO_2$ emissions therefore follow a more complex trend than that of energy demand. They may have peaked in terms of emissions per head in 1973 (along with the energy demand peak) but it is not clear that the rate of growth will slow down at the same rate as that of energy consumption.

- In other words, it is in principle possible to decouple economic growth and $CO_2$ emissions, but we cannot rely on this happening automatically as economies grow; policy intervention may be needed.

### *6.4 Energy services*

- It is not just the fuels themselves which have changed fundamentally over time; it is also the energy services being provided. The trend involves not just an increasing demand for familiar services but the development (and rapid growth) of new services, many of them previously unknown.
- In pre-modern Europe, the main energy services could be summarised as muscle and heat. Initially, the industrial revolution led to a growth in physical work and increasing amounts of power being needed for machinery. However, there soon followed a shift to different sorts of energy service, such as lighting and transport. Consumption of these services has increased by almost unimaginable amounts since 1750. Looking forward from today, we have no reason to believe that we can forecast what energy services will be used hundreds of years from now with any accuracy.
- Analysis in terms of specific services such as lighting and appliance use may therefore be inadequate to cover the range of possible new services. In the future, it is likely that energy will increasingly be used to provide a range of services which require intelligence and save time.
- Since there is no limit that can be set on the possible extent of human intelligence and creativity, and since efficient use of time is, according to most forecasts, going to be ever more important as the future progresses, there is therefore no reason to believe that energy demand will ever saturate.
- There is much more uncertainty about current long-range energy forecasts than is acknowledged. Not only do we not know what the overall growth in population and output might be over the centuries, we do not know the structure of future economies or the energy sources and energy services they will use. We are relying too much on what are essentially extrapolations of the present, paying attention to energy trends which may seem well established to us but which, on a long view, are recent phenomena. We are not doing enough to explore possible scenarios for the future or to identify and anticipate possible shifts in energy demand and use.

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