much greater than for the UK, and at some 750 TWh (trillion kWh) a year it puts the USA easily in first place world-wide.

Fifty years ago the USA was self-sufficient in energy, as it had been throughout most of its recorded energy history. This was also the case for the UK, as we've seen, and comparison of Figures 2.14 and 2.8 reveals two countries whose thirst for oil in the period from about 1950 to 1970 was leading to similarly growing gaps between energy production and consumption. However, the similarity is only superficial and hides one crucial difference. In the early 1970s the UK was just starting to develop her indigenous oil resources. The US, in contrast, was beginning to exhaust hers, as Figure 2.15 shows. These two facts account in large part for the difference in self-sufficiency of the two countries at the end of the century.

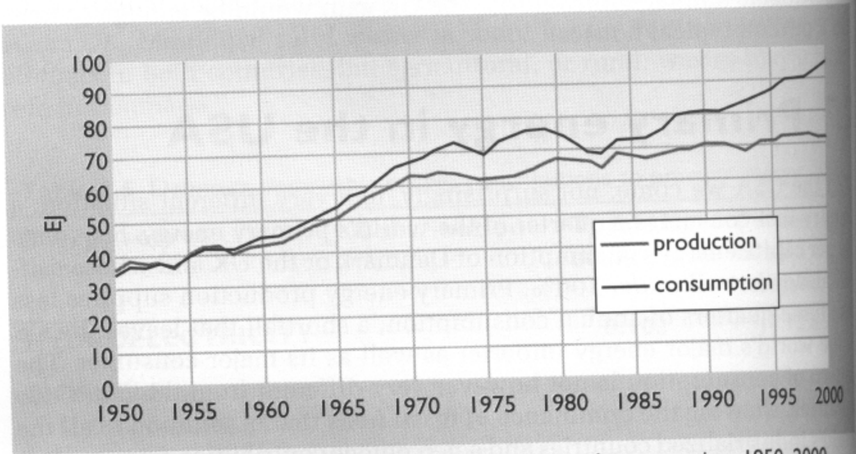


Figure 2.14 USA: Annual primary energy production and consumption, 1950–2000

Figure 2.15 bears closer study. At the start of the 1970s, production from the existing oil fields in the US reached its peak, and output was already falling when the first dramatic increase in world oil prices occurred in 1973. The extent to which the country had become dependent on the oil producers of the Middle East was made obvious to everyone, and for a couple of years consumption fell. It soon resumed its rise, however, encouraged in part by the development of the Alaskan oil fields, whose

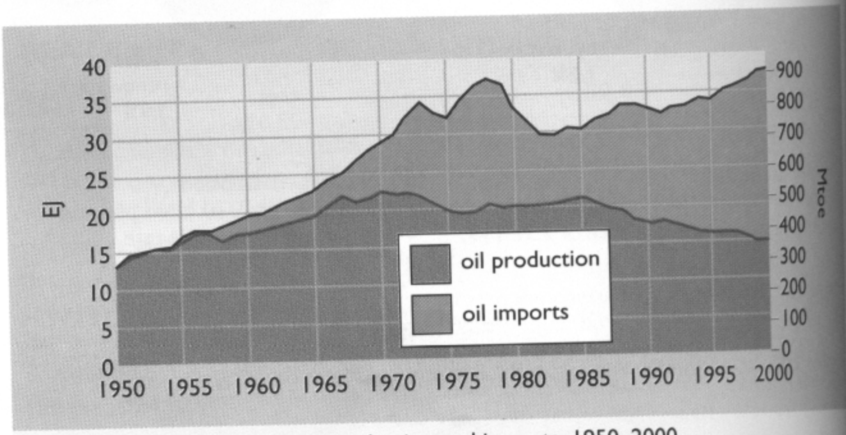
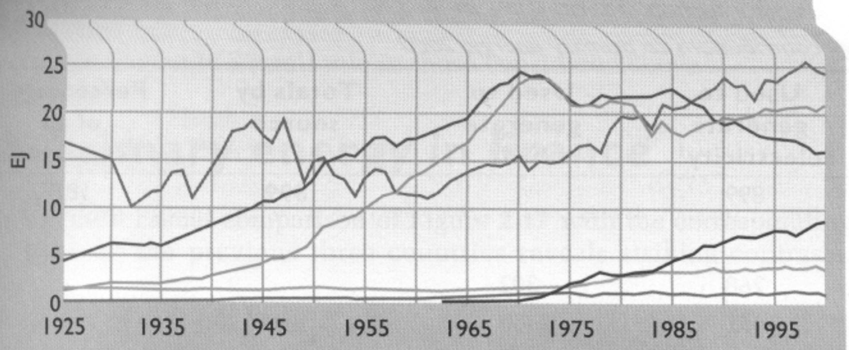


Figure 2.15 USA: Annual oil production and imports, 1950–2000

output delayed the fall in national production for about a decade. The further oil price increase in 1978 and the recession of the early 1980s brought about a more serious fall in consumption. However, as the graphs show, this was only temporary, and the steady rise in consumption throughout the 1990s resulted in the greatest shortfall ever by the end of the century.

Comparison of Figure 2.16(a) with Figures 2.9(a) and 2.12(a) shows at least one other striking contrast. We have looked at Denmark, with essentially no coal industry at any time, and the UK, once living on coal but with the industry in decline for the past fifty years. Now we see the US, with energy contributions from oil and from gas overtaking coal as early as the 1950s but coal *reversing* this situation in the 1990s. In this case, however, the USA is more characteristic of the world as a whole. As we'll see in later chapters, the demand for electric power rose rapidly throughout the second half of the twentieth century in almost every country, and coal, still the principal fuel for most of the world's power stations, experienced a corresponding growth in output. Britain, with its 'dash for gas' is therefore an exception, and Denmark, for reasons discussed in the next chapter, is another. (Our next country, France, is a third, for yet other reasons.)

(a) Annual production



(b) Annual consumption

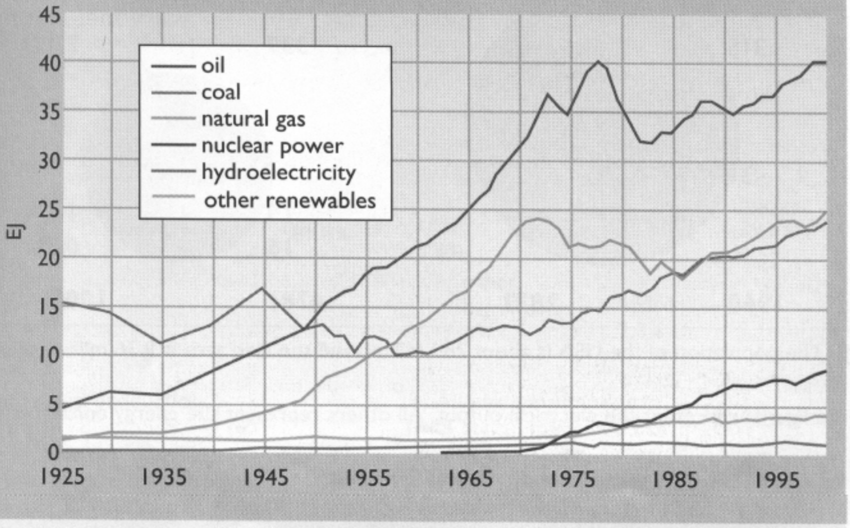


Figure 2.16 USA: Primary energy by source 1925–2000

Renewables in the USA

On a *per capita* basis, the USA is remarkably similar to Denmark in the broad features of its use of renewables. The average American and the average Dane both use the equivalent of about 4700 kWh a year of primary energy from renewable sources, and in both cases roughly three-quarters of this comes from the combustion of waste products – either for electricity production or for direct use of the heat. In both cases again, most of the remainder comes from one source, with the difference that in the US this source is water and in Denmark it is wind. The actual magnitudes of these contributions are of course very different – as are the differences in scale of the two types of plant, from the megawatt or so of the latest 'large' wind turbine, to a thousand times this for a large hydroelectric plant such as the Grand Coolee on the Columbia River. The US renewables total does include a contribution from wind power (mainly from wind turbines imported from Denmark), and comparison of Tables 2.5 and 2.6 shows that the annual output from this source is in fact very similar for the two countries (and about five times the corresponding figure for the UK.)

For a country with very large sunny areas, we might be surprised that the solar contribution is a mere 1.5% of renewable energy – about a thousandth

Table 2.6 USA: renewable energy contributions to primary energy, 2000

Energy source	Used to generate electricity[1]	Used to generate heat	Totals by source	Percentage of all renewables
HYDROELECTRICITY	899		**899**	18.8%
BIOFUELS				
wastes[2]	268	302		
wood[3]	431	2308		
alcohol fuels[4]		147		
Biofuels total			**3455**	72.3%
GEOTHERMAL	315	22	**337**	7.0%
SOLAR ENERGY				
solar heating		42		
photovoltaics	31			
Solar total			**74**	1.5%
Wind	16		**16**	0.3%
TOTALS	**1960**	**2821**	**4781**	**100%**

Data: All energies are in petajoules (PJ). The population of the USA is about 280 million and the land area is 9.36 million square kilometres.

1 For hydro, wind and photovoltaics the figures represent the electrical output. All others represent the energy content of the fuels.

2 Includes MSW, landfill gas, sewage, agricultural wastes (except woody wastes), tyres, etc.

3 All wood, including wastes.

4 Ethanol from vegetable matter, to be blended into motor gasoline. (See Chapter 7 and Boyle, 1996.)

(Source: EIA, 2001)

of the country's total primary energy. In terms of energy produced per square kilometre of land area it is however some five times greater than the Danish figure (and thirty-five times Britain's). As the data in Table 2.6 show, the US, unlike the other two countries, does have an appreciable geothermal resource. Geothermal power plants in the western states extract some ninety billion kilowatt-hours of heat from the ground annually in the form of superheated steam, providing sufficient electricity for a few million households.

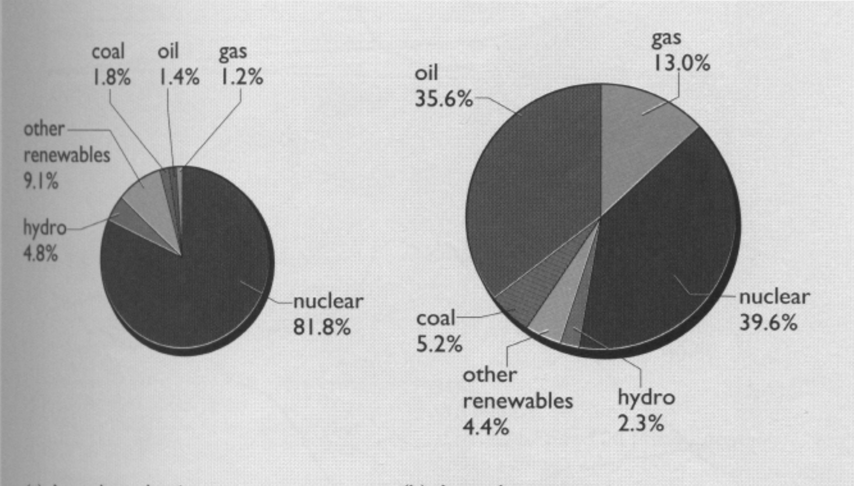
Review

We have tended in this discussion to emphasize the contrasts between countries, but a review of Figures 2.7, 2.10 and 2.13 shows that, whilst the total quantities of energy and the degrees of self-sufficiency may be very different, the general patterns of *consumption* are not dissimilar. Each country meets roughly two-thirds of its demand for primary energy from the two premium fossil fuels, oil and gas, and about another fifth from coal. And as we saw above, the pattern for the world as a whole is again similar – not surprisingly, as world consumption is dominated by industrialized countries such as these.

However, not every country has chosen – or has been able – to adopt this pattern, and we end the present survey with very brief accounts of two whose primary energy consumption includes major contributions from sources that play only a small role in those considered above.

2.8 Primary energy in France

Even the most casual comparison of Figure 2.17 with the corresponding pie charts for the previous three countries reveals striking contrasts.



(a) Annual production
Total production: 5.5 EJ or
131 Mtoe per year,
or an average continuous
rate of 174 GW.

(b) Annual consumption..
Total consumption: 11.3 EJ or
270 Mtoe per year,
or an average continuous rate of 358 GW.
Per capita consumption: 192 GJ per year,
or an average continuous rate
of 6.1 kW per person.

Figure 2.17 France: Primary energy production and consumption, 2000

This time they are not in the quantities, as primary energy consumption *per capita* in France is only a little greater than in Denmark and the UK. The differences are in the extremely low self-sufficiency – less than 50% –

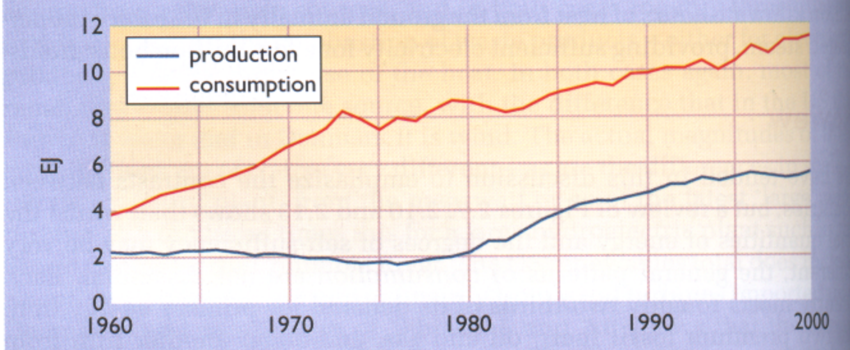
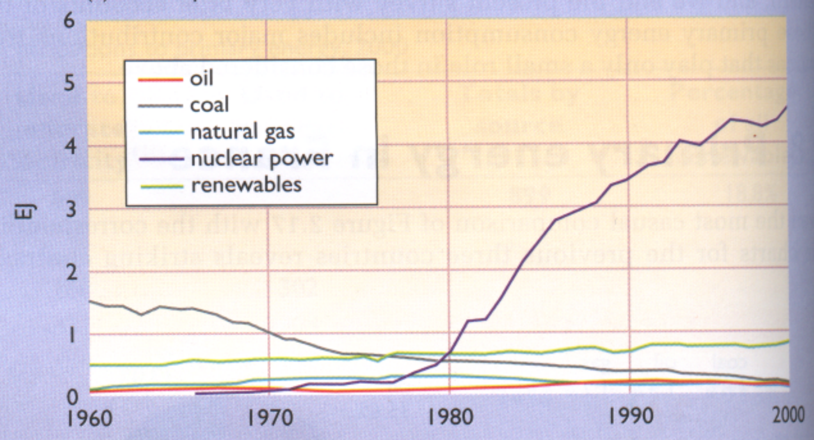


Figure 2.18 France: Annual primary energy production and consumption, 1960–2000


(a) Annual production

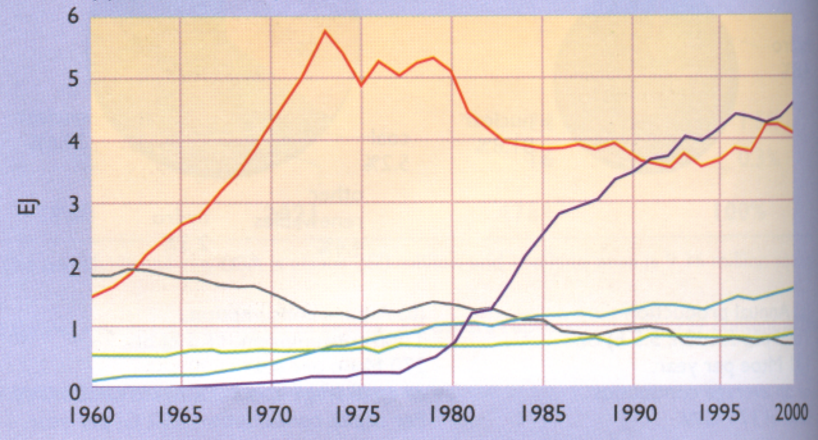
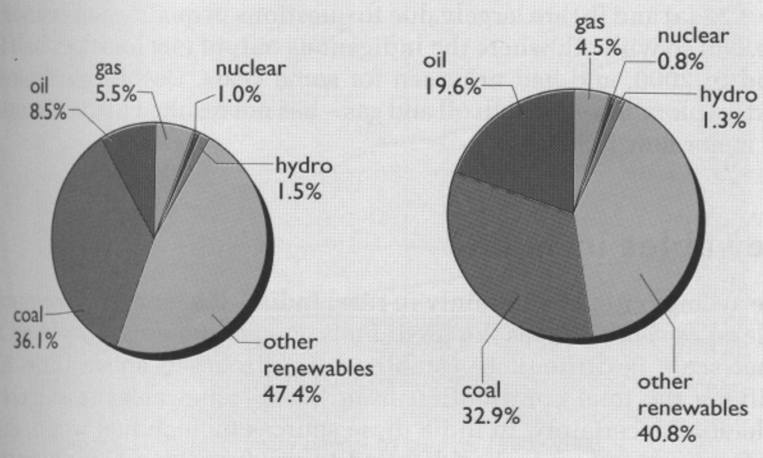

(b) Annual consumption

Figure 2.19 France: Primary energy by source, 1960–2000 and in the major role played by nuclear power. The reasons are easy to see in the energy production data. France has few indigenous fossil fuels but has chosen to develop her nuclear power industry. This can of course only partially compensate for the missing oil or gas resources, and the country is left with imported oil and gas accounting for half her primary energy consumption.

Figures 2.18 and 2.19 show the development of this situation over recent decades. We see the now familiar growth in oil consumption during the 1960s, accompanying a slight fall in indigenous coal production; but France, unlike the UK or Denmark, was not about to be saved by the discovery of oil or gas. Another significant factor was that at the start of this period large areas of rural France still lacked a mains electricity supply. The consequences of these factors, and the development of the French electricity industry, are discussed in more detail in the next few chapters.

2.9 Primary energy in India

India is the world's second most populous country and its sixth largest consumer of energy. Over the past twenty years, the population has been growing at just under 1% a year and annual primary energy consumption at about 2.5% for the 'conventional' resources only, a discrepancy between the two growth rates that is not unusual for a developing country. In the year 2000, India's per capita consumption, for the conventional resources only, was slightly over 12 GJ a year – effectively an average continuous supply of just under 400 watts per person, or about a thirtieth of the US average.

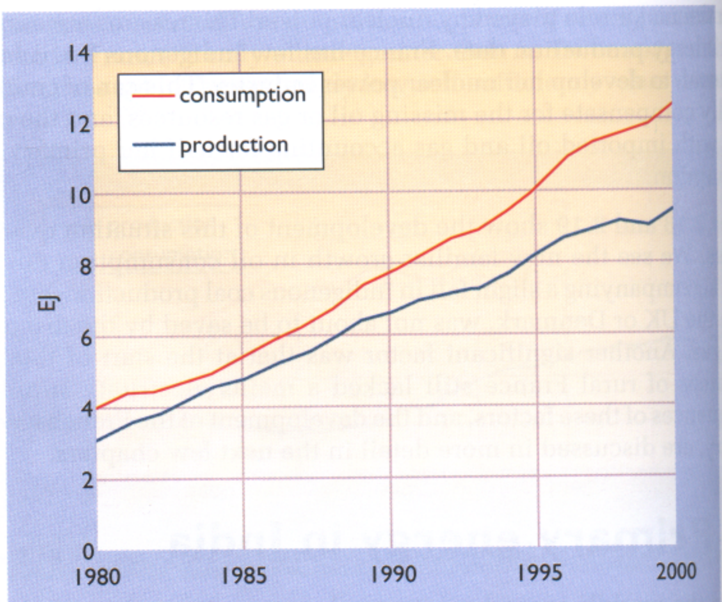


(a) Annual production
Total: 18 EJ or 430 Mtoe per year,
or an average continuous
rate of 0.57 TW.

(b) Annual consumption
Total: 21 EJ or 500 Mtoe per year,
or an average continuous
rate of 0.66 TW.
Per capita consumption: 21 GJ per year,
or an average continuous
rate of 0.66 kW.

Note: See the main text for discussion of the renewables.

Figure 2.20 India: Primary energy production and consumption, 2000



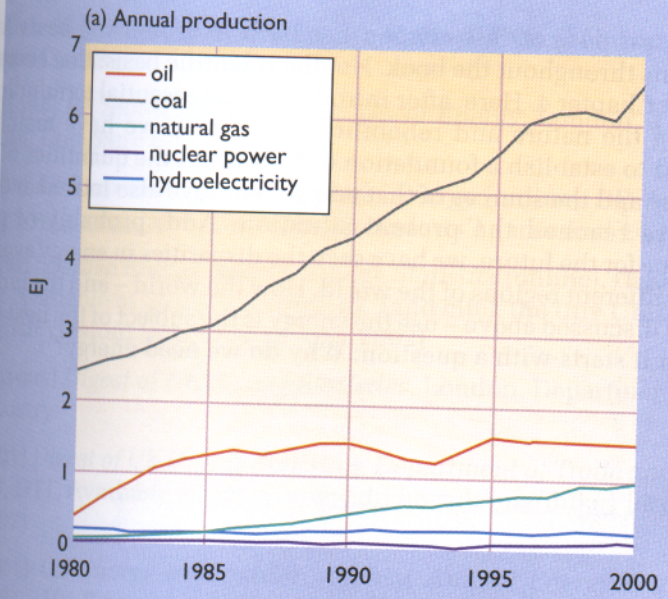
Note: These totals do not include bioenergy.

Figure 2.21 India: Annual primary energy production and consumption, 1980–2000

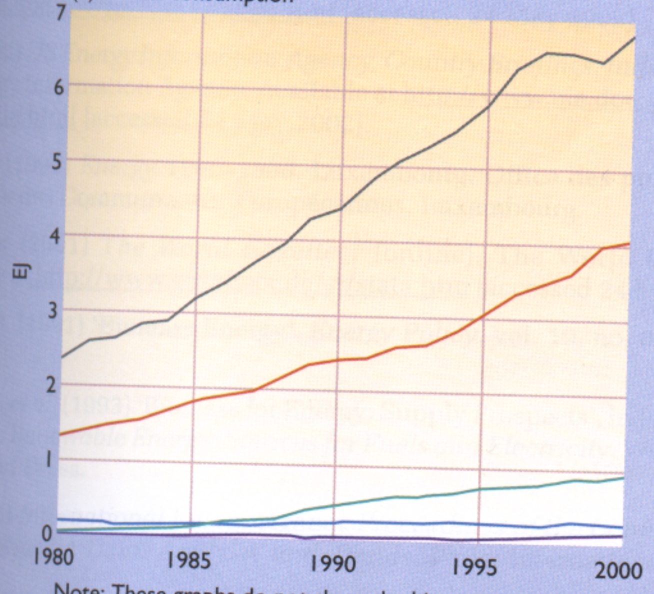
India's overall energy self-sufficiency is 86%, but if the renewables are excluded, the figure falls to 80%, and as Figure 2.21 shows, the shortfall in primary energy has been increasing steadily over the past few decades. The country has a large coal resource, and the coal imports implied by Figure 2.22 (a) and (b) are largely due to questions of quality and economic factors. Not so with oil, where the indigenous output met less than half the demand in 2000, and had not risen for some years. Despite government support, exploration – for both oil and gas – has not resulted in the discovery of any major new fields.

Renewables in India

For the average citizen – certainly in rural India – the renewable resources are at least as significant as the fossil fuels. Exactly how significant on the national scale is difficult to establish. As discussed above (Box 2.6), quantifying the total contribution from 'local' renewables is subject to considerable uncertainty. In India these sources include fuel wood, dung (dried for direct use as fuel or digested to produce 'biogas' for burning), bagasse (sugar cane fibre), rice husks and other agricultural residues. Estimates of the total annual bioenergy contribution have tended to lie in the range 5–15 GJ per person per year (Hall 1991, EIA 2002), which implies 5–15 EJ for the current Indian population of one billion. The figure of 8.5 EJ used in Figure 2.20 is weighted towards the more recent estimates, but should be regarded as uncertain within a range of at least ± 20%. Fuel wood probably accounts for about half the total bioenergy, with dung and other agricultural residues contributing most of the remainder.



(b) Annual consumption



Note: These graphs do not show the bioenergy contributions.

Figure 2.22 India: Primary energy by source, 1980– 2000

Some renewables are of course better documented, including large-scale hydroelectricity (shown separately in the graphs here), and smaller contributions from small-scale hydro, solar energy and wind power. India's installed capacity places her amongst the world's top half a dozen countries in terms of wind power, but the output accounts for no more than a percent or so of the renewables total.

2.10 Summary

The main purpose of this chapter has been to establish a basis for lat discussions throughout the book. Not the scientific basis: that comes lat starting in Chapter 4. Here, after introducing the essential terminology an discussing the nature and reliability of the data, we have mainly bee concerned to establish a foundation of facts about the quantities of ener used today and the sources of that energy. We have also looked at the pas at how we reached the present situation. And, probably of greates importance for the future, we have seen the disparities in energy availabili between different regions of the world. How the world – and the individu countries discussed above – use the energy is the subject of the next chapt and again it starts with a question: Why do we need energy?

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3.1 Primary, delivered and useful energy

The previous chapter has described the flows of large amounts of primary energy, yet as pointed out in Chapter 1, what we as consumers really require are **energy services**, such as warm homes, cooked food, illumination, transport, and manufactured articles. A great deal of industrial and commercial activity is involved in supplying these 'end products' from the primary energy sources discussed in Chapter 2. The questions we need to ask are: what are the essential 'useful' forms of energy that we need; how much energy is lost in supplying this; and what exactly are we finally paying for?

Lighting is a very good example. If you want to read at night you need reasonable illumination. You could light a candle and produce light directly from fuel (candle-wax). Candles are not very bright, of course, and since a candle converts only about three ten-thousandths (0.03%) of its fuel into light, it is not a very efficient way of doing things. You are more likely to turn on an electric light.

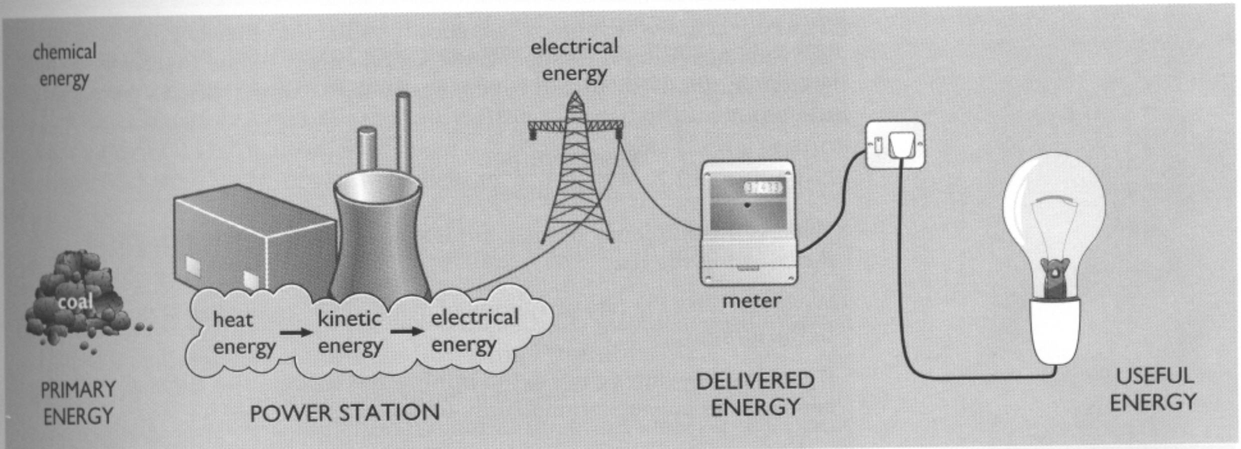

Figure 3.1 Primary energy, delivered energy and useful energy

As we have seen, what happens when you do this is a succession of energy processes, with energy being lost as waste heat at every stage. At the input stage is the primary energy source, which might be coal, oil or gas in the naturally occurring state in the ground or under the sea. Alternatively, the primary energy source might be the heat produced in a nuclear reactor. Taking coal as our example, we find that by the time the coal reaches the power station typically about 2.5% of this energy has already been used in mining and transporting it. Similar losses apply to oil, which may have been transported thousands of miles by sea and will also have been refined, and to natural gas, which may have been pumped to western Europe through pipelines stretching from distant Siberia.

In the power station the chemical energy of the coal is converted to heat, then into the kinetic energy of the steam turbines and finally into electrical energy. As we have seen, only about 30–40% of the energy of the fuel emerges as electricity. Some of this is likely to be lost as heat in the transformers and wires of the electricity distribution system, before it reaches your electricity meter. At this point it becomes **delivered energy**. This is what you actually receive and what you pay for – about a third of the primary energy extracted at the coal mine.

The wastage does not stop there. The electrical energy has to be converted into light of a suitable combination of wavelengths for you to read your book. Ultimately this light is the **useful energy** that you need.

If you were determined to be energy efficient, you could read by the orange light of a street lamp. These can convert about 30% of the electrical energy into visible light. But you are more likely to choose the more acceptable light of an incandescent lamp (a normal filament bulb). This however will produce only about 5 watts of visible light for every hundred watts of electric power, the rest being lost as heat. So, overall, for every gigajoule of primary energy that left the coal mine, only about 16 MJ have been converted into light (see Box 3.1); the other 984 MJ have become waste heat. This may sound appallingly wasteful, but is still fifty times more efficient than using candles!

BOX 3.1 Conversion efficiency

The conversion **efficiency**, often simply called the **efficiency**, of any energy conversion system is defined as **the useful energy output divided by the total energy input**. In practice it is very common to express this as a percentage of the input.

$$\text{Efficiency} = \frac{\text{Energy output}}{\text{Energy input}} \times 100\%$$

What is the efficiency of the complete coal-to-light conversion process described in the text?

We'll consider the fate of 1 tonne of coal: 28 GJ (gigajoules) of primary energy in the ground.

If 2.5% of this energy is used in mining and transporting the coal, the energy entering the power station is only 97.5% of this:

$$\text{Energy entering power station} = 0.975 \times 28 = 27.3\ \text{GJ}$$

If we take the fuel-to-electricity efficiency of a modern coal-fired power station (commonly referred to as the **thermal efficiency**) to be 35%:

$$\text{Electrical energy leaving the power station} = 0.35 \times 27.3 = 9.56\ \text{GJ}$$

On average, about 7.5% of this will be lost as heat in transmission in the wires and transformers or the way to the user, who receives only 92.5%, so

$$\text{Delivered electrical energy} = 0.925 \times 9.56 = 8.84\ \text{GJ}$$

But an incandescent light bulb turns only 5% of this into light (see the main text), so

$$\text{Useful light output} = 0.05 \times 8.84 = 0.44\ \text{GJ}$$

Thus an input of 28 GJ of primary energy produces an output of 0.44 GJ of useful light energy

$$\text{Overall energy efficiency} = \frac{0.44}{28} \times 100\% = 1.6\%$$

This theme of increasing efficiency of energy use is a recurring one. Although it may seem that we are currently living in a 'gas-guzzling' society, the truth is that we would probably be guzzling even more if it hadn't been for many significant improvements in energy efficiency, particularly over the last 150 years.

3.2 The expanding uses of energy

As we've seen in the previous chapter, the world use of energy has risen enormously over the past two centuries. This has been the result of a growing world population multiplied by an increasing energy use per person. For those who live in an industrialized world of cheap, readily available energy, it can be difficult to imagine what life would be like without it. It is worth, therefore, reflecting on exactly what society uses energy for and what changes have taken place over the broad time scale.

There are many ways of classifying these uses. Modern statisticians like to categorize them by the sectors of the economy; industrial, commercial, domestic and transport. We will look at these figures and the detailed changes over the last 40 years later in this chapter. Looking back further in time, Vaclav Smil (Smil, 1994) has made estimates of energy use per head of population (or *per capita*) for different societies in history. He has categorized the uses according to food, household, production, transport and services, although in practice, as in any other classification system the boundaries may blur into each other. Figure 3.2 shows figures for the energy consumption of the UK in 2000, together with Smil's estimates for five past societies:

- Europe in 10 000 BC - a stone-age society of hunter-gatherers living in wooden huts.
- Egypt in 1500 BC - a bronze-age culture with settled agriculture, organized irrigation and enough spare time to build the Pyramids.
- Han Dynasty China in 100 BC - another agricultural society, also with organized irrigation, but which had mastered the art of making cast iron.

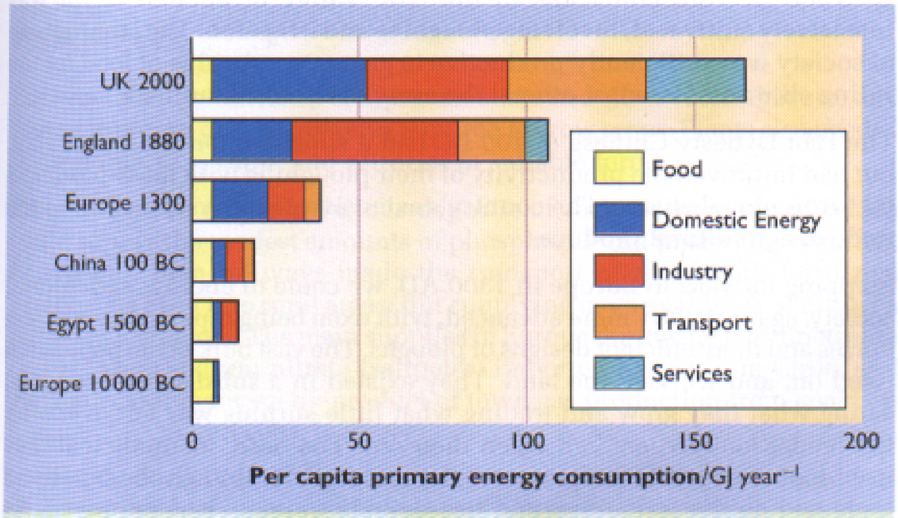

Figure 3.2 Per capita primary energy consumption for different societies (adapted from Smil, 1994). In the UK 2000 bar, energy loses such as those in electricity generation are included under each sector

- Europe in 1300 AD - an advanced agricultural society, using wrought iron smelted with charcoal, trading coal by sea and capable of building large cathedrals. This is the world of Chaucer's Canterbury Tales. The UK population was then about 6 million.
- England in 1880 - Victorian industrial society, fuelled by coal and driven by steam, criss-crossed with new railways, exporting enormous amounts of coal to the world, busy inventing a host of new chemical and industrial processes, and just about to embark on exploiting mains electricity. The UK population was then about 30 million, about half the current figure.

Each society consumes more energy than the previous one, yet it is not a matter of using more energy for every category of use, rather that new uses arise and expand. Moreover, they are likely to arise in one country, such as agriculture in Egypt or industrial society in Victorian England, and then spread across the world. Let us look at each category of energy use in turn.

Food

This is the first and ultimately most important category in Figure 3.2. The actual edible food energy or dietary energy needed by a human being is about 10 MJ per day, about 3.6 GJ per year. Obviously if you are involved in hard physical labour, then you will need more than this. This figure does not normally appear in energy statistics, though the energy to grow, harvest, package, transport and cook food does.

For prehistoric European humans in 10 000 BC, life was a matter of hunting wild animals and gathering naturally growing food plants. The energy used to do this was your own personal hard effort. If you could gather enough food energy to supply this, you prospered, if you couldn't you would starve. In addition to this the energy of wood was used to cook the food and to heat the relatively primitive homes, wood huts or caves.

The first agricultural societies grew up around 3000 BC in Mesopotamia, planting crops and using domesticated animals such as oxen to carry heavy loads and augment the hard human physical labour of ploughing and raising water for irrigation. These skills slowly spread to surrounding countries. By 1500 BC, the landscape of the Nile Valley of ancient Egypt was intensively cultivated, involving ploughing and irrigation. The farming base of society was sufficiently productive to generate a surplus of food for the ruling elite and (amongst others) the army of Pyramid builders.

The Han Dynasty Chinese of 100 BC had a similar intensive agriculture, but had improved the productivity of their ploughing with mass-produced cast-iron ploughshares. The country's extensive canal system allowed the trade of agricultural produce.

Stepping forward to Europe in 1300 AD, we come to another agricultural society, again slightly more advanced, with oxen being replaced by stronger horses and more efficient designs of ploughs. The vast bulk of the population lived on, and worked, the land. They existed in a **subsistence economy**, eating what they grew and trading what little surplus was left over after the feudal landowners had taken their cut. The basic methods that they used had changed little for over a thousand years, though the quality of tools and ability to harness and use draught animals had improved. By this time, water power had also been harnessed for irrigation and grinding corn and the earliest windmills were starting to become common.

Figure 3.3 A traditional irrigation windmill at work in Crete (photo Bob Everett)

By the time we reach England in the 1880s society was radically different. Agriculture was embarking on changes every bit as drastic as those taking place at the same time in industry. The new job opportunities in urban factories, coupled with competition from imported food brought by steam ship and railway, led to a continuing decline in rural population. By this time the bulk of the English population were living in rapidly growing manufacturing cities, swelled by a continuing drift of manpower from the countryside. Yet all these people had to be fed. Although farming efficiency had been improved in the eighteenth century by introducing larger and more powerful breeds of horse, the nineteenth century saw the introduction of artificial fertilizers and farm mechanization. The idea of modern farms as 'agribusiness' presiding over 'corn deserts' provokes angry debate today, but it is the end product of a set of trends set in motion over a hundred years ago.

Fertilizers

Eighteenth and nineteenth century chemists had discovered that sun and rain were not the only ingredients required to grow crops. Plants also needed phosphorus, potassium and nitrogen in suitable forms.

From the 1840s onwards various deposits of rocks were quarried which could supply the modest amounts of phosphorus and potassium required. Canals and then railways made the transport of these bulk fertilizers practicable, even into rural areas. But supplying large quantities of nitrogen remained a problem. The main supplies in Europe during the late nineteenth century were sodium nitrate (saltpetre) imported by sea from Chile, and ammoniacal liquors – a by-product of town gas production from coal (see Chapter 7 – Oil and Gas).

In 1914 the First World War created a nitrate supply crisis for Germany. Its chemical industry came to the rescue with the Haber-Bosch process, manufacturing ammonia (NH_3) using nitrogen in the air and hydrogen from town gas. Initially this was needed for the manufacture of explosives for the war, but afterwards it was seen that the process had a genuine 'swords into ploughshares' application by providing nitrogenous fertilizer. Initially the process was extremely energy intensive. In 1930 an ammonia plant would have consumed the energy equivalent of 9 tonnes of oil to make one tonne of ammonia. Since then there have been extensive improvements. A modern (1994) plant only requires 23 GJ (about 0.7 tonnes of oil equivalent) per tonne of ammonia. Nevertheless the energy involved in fertilizer manufacture remains a major input in modern intensive agriculture.

The immediate rewards of using nitrate fertilizer were increased yields with existing strains of crops. In 1300 typical English yields of wheat were less than 1 tonne per hectare of land. By 1880 they had been more than doubled. Yet even these yields have been increased by the breeding of special strains of crops capable of making use of very high levels of nitrogen in the soil. British wheat production reached yields of 4 tonnes per hectare in the 1970s and at the time of writing the figure stands at around 8 tonnes per hectare.

This massive use of synthetic nitrogen fertilizer is now world-wide, and it has been estimated (Smil, 1994) that at least one-third of the protein in the current global food supply is derived from the Haber-Bosch process. The disadvantages of this high nitrogen input have been the **eutrophication** or poisoning of watercourses with high nitrate levels, and emissions of nitrous oxide, a greenhouse gas. The latter is discussed in Chapter 13, Penalties.

Looked at one way, this extra fossil fuel energy input is simply an aid to improving the efficiency of take-up of solar radiation into useful farm produce. A more pessimistic viewpoint would see this as '*a sad hoax, for industrial man no longer eats potatoes made from solar energy, now he eats potatoes partly made of oil*' (Odum, 1971). The question of whether or not an agricultural process can produce more energy in the crop than the fossil fuel inputs taken to grow and process it is an important one, particularly for the development of biofuels such as ethanol and bio-diesel.

Farm mechanization

While Victorian industry ran on coal, agriculture ran on horses and human muscle-power and this continued into the 20th Century. By 1901 Great Britain had 3.5 million horses of which of which 1.1 million were employed on farms. About 30% of lowland farm area was devoted to their keep, 10% just for farm horses. This horse population was matched almost one to one with about a million full-time farm workers plus an army of casual labour, mainly from the cities, at harvest time. Mechanical assistance was limited to a few low-powered steam engines used for threshing and grinding. Although horse-drawn reaping machines had been introduced in the UK in the early years of the nineteenth century their use was limited by the small size of fields and narrow lanes. In the US, space was not a problem. By the end of the nineteenth century fully automatic horse drawn combine harvesters were in use. The largest needed 40 horses to operate but could harvest a hectare of wheat in 40 minutes.

Farm mechanization in the UK was very slow to develop. By 1920 there were only 10 000 farm tractors in the country. They were outnumbered nearly 100:1 by horses. There was little incentive for mechanization. During the 1920s and '30s there was high unemployment and labour was cheap. British agriculture was in a very depressed state, competing with cheap imported food.

However, in 1939 all that changed. World War II brought a serious food blockade and food rationing. Meat became a tightly rationed luxury, and land that had been pasture for livestock was ploughed up to grow more vegetables for direct human consumption. The war drained manpower from the land, and productivity could only increase by more mechanization.

After the War, British society had changed. Post-war reconstruction required man-power in factories. Labour prices rose compared to the price of farmland and mass-production techniques had reduced the price of farm machinery. It no longer made economic sense to employ whole armies of agricultural labourers when a few men and machines could do the same job. A modern tractor can plough a field ten times faster than its horsedrawn equivalent. Even so, it is perhaps surprising that it was not until the 1950s that the number of tractors in Britain exceeded the number of farm horses.

Figure 3.4 A modern combine harvester rapidly chews its way through an Essex wheat field

Again, looked at one way, the mechanization of farms has meant an injection of fossil fuel energy. On the other hand, removing the horse has freed all their grazing land for further agricultural production. Smil has estimated that feeding America's farm horses required 25% of their cultivated land. One key advantage of the tractor is that you can switch it off! Once the ploughing or harvesting is done it can be put away in a barn for next year. A horse keeps eating, whether or not you use it! Another 'benefit' is that the large workforce is no longer needed, theoretically freeing it for other uses. This is fine if there is alternative employment, but in many cases it has just continued the trend of the depopulation of the countryside and growth of cities.

The food shortages of World War 2 have left a deep mark on UK (and EU) agricultural policies. There are extensive subsidies to promote farm production which have implied high levels of energy and fertilizer use. At the time of writing, the UK is self-sufficient in a wide range of basic foodstuffs. The energy price paid for this amounts to a modest 1 GJ per year per capita for the fuel energy to run UK farms and about the same amount again in manufactured fertilizers.

Domestic energy

Compared to the modern centrally-heated, electrically-lit society, the past was cold in winter, draughty, smoky, dirty and very dark after sunset. For prehistoric man, home was likely to be a cave or a wooden hut. Later societies developed their building skills with bricks and mortar and metal woodworking tools to produce the house as we know it today. Yet central to the home was the *fire* for cooking, heating and lighting.

Heating, washing and cooking

The Roman elite may have had central heating, but most of their expertise disappeared in the dark ages. In mediaeval England, the use of fire was a rather unruly and dangerous affair (especially so in a wooden house) and must have been extremely energy inefficient. According to Bowyer (1973), there appears to be no evidence of chimneys in England before the 12th Century. Neither the London Building Byelaws of 1189 nor of 1212 mention fireplaces or chimneys, even though the main reason for their introduction was to reduce the risk of fire. Buildings simply had permanently open smoke-holes in the roof. The indoor air quality must have left a lot to be desired and cooking could be a serious fire hazard. The Great Fire of London in 1666, which destroyed over 13 000 houses, started in a pie shop in Pudding Lane. As with other, later, energy-related catastrophes, it led to a series of Acts of Parliament, in this case, specifying how chimneys were to be built, at least to be safe, if not necessarily efficient.

Figure 3.5 The coal fire was the heart of the home for heating and cooking – a reconstruction in the Beamish Museum, Co. Durham

The modern fireplace is a product of careful design, originating in the sixteenth century. The nineteenth century fireplace shown in Figure 3.4 is also a masterpiece of cast iron construction, providing **space heating** (that is heating of the living spaces) as well as an oven for baking and a place to boil kettles and saucepans. **Domestic hot water** for washing and cleaning also had to be produced in this manner – today we would use a dedicated gas or electric water heater.

In rural Britain, wood would have been the normal fuel used in such a fireplace, but by the seventeenth century, coal was widely used in cities (see Chapter 5). The hearth was the centre of the home, and especially after dark, not least because of the expense of lighting any other room (see below). This fire effectively needed to be kept burning all year round for cooking and water heating. In summer it would make the living room too hot, and in winter it would be too cold. The joys of warm rooms and running hot water, although technically feasible, passed most of Britain by until the latter part of the twentieth century. This was stoically accepted as part of life. The Reverend Francis Kilvert, a Herefordshire clergyman, describes getting up on Christmas Day, 1871:

> ...It was an intense frost. I sat down in my bath upon a thick sheet of ice which broke in the middle into large pieces whilst sharp points and jagged edges stuck all round the sides of the tub ..., not particularly comforting to the naked thighs and loins, for the keen ice cut like broken glass. The ice water stung and scorched like fire. I had to collect the floating pieces of ice and pile them on a chair before I could use the sponge and then I had to thaw the sponge in my hands for it was a mass of ice...

The open coal fire, with a thermal efficiency of about 25%, remained the normal mode of heating in UK homes until the 1960s, much to the derision of visitors from the Continent and US where central heating was considered normal. Central heating only reached the bulk of UK homes after the introduction of North Sea natural gas in the late 1970s.

The introduction of town gas made from coal in the early nineteenth century was initially for lighting. It soon became apparent that it was an ideal controllable fuel for cooking. Unlike a coal stove, a gas cooker could be turned on and off quickly. Cooking, with all its attendant smells and mess, could be carried out wholly in the kitchen, instead of spilling over into the living room with its coal fire devoted to space heating. This in turn influenced house design, making the kitchen and living/dining rooms into completely separate entities.

The Victorian housewife's life was not easy. Even middle-class families would aspire to have a female domestic servant (or 'scivvy') whose life was even harder. Before the advent of modern detergents and washing machines, cleaning clothes was mostly a matter of hard physical labour, scrubbing them in hot water with soap. Before the electric vacuum cleaner, house cleaning was an endless inefficient chore of chasing after dust and grit with a dustpan and brush.

The First World War in 1914 was a turning point. Millions of men were drafted into the Armed Forces creating a severe labour shortage. Women left domestic service to work in the munitions factories where they enjoyed considerable equality with men. After the war they did not want to return to the old ways as domestic drudges. There was a 'servant shortage'. The market was ripe for selling 'labour saving appliances', vacuum cleaners, washing machines, electric irons, etc., a process which has continued to the present day.

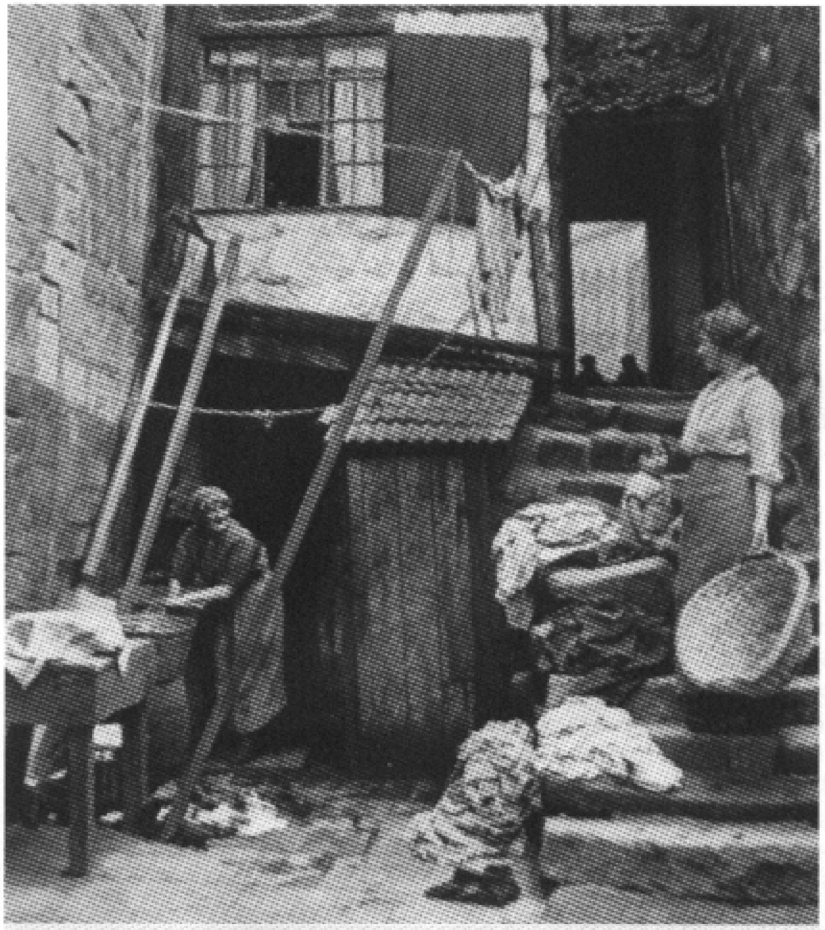

Figure 3.6 Hard female labour – before washing machines and modern detergents washing clothes meant hard scrubbing with hot water and soap

Preserving and processing food

Today, 'food' is something that we buy from a supermarket, usually wrapped in plastic. We are likely to deposit it into our domestic refrigerator and, at mealtimes, transfer it rapidly to the plate via a microwave oven. At the extremes it has become an industrial product, processed and packaged by machines and transported vast distances.

In the past the preserving and processing of food was something that largely took place in the home. Before about 1000 AD, even basic tasks such as the grinding of corn would have been done by hand in the home with a small hand grindstone. The introduction of water, wind and horse-powered mills turned this from a home activity to a (local) industrial one. Also, given the fire risks in a mediaeval home, baking was a task that was safest to leave to a professionally-run bake-house.

Dealing with meat was a particular problem. Animals could either be slaughtered and preserved with salt or kept alive for as long as possible before being served up. In the countryside this didn't pose too much problem. In the expanding cities, it created chaos. Even up to the mid-nineteenth century herds of cattle were driven on the hoof through the streets to city-centre markets to be sold and then slaughtered. This was a road traffic nightmare, but also meant that a whole host of food-rendering industries naturally grew up, also in the cities. All these required energy for process heat. Animal fats were rendered down to make, amongst other things, tallow for lighting fuel and bones boiled to make glue. One of the smelliest processes was considered to be boiling down blood to make fertilizers.

The arrival of railways and cold storage by the end of the nineteenth century was a godsend. Cattle markets, the new cold stores and all the smelly processing industries were removed to their current locations in industrial estates well away from the noses of the more well-to-do householders.

This freed up city centres as the home for the services sector, in particular banking and shopping.

Although 'machine' refrigeration as we know it today is a late nineteenth century invention, it did not really take off until the early twentieth century because bulk ice was a globally traded commodity. In 1900 the UK imported half a million of tonnes of ice from Norway and even some from the US (see Weightman, 2001). The food distribution chain relied on blocks of ice bought along with the food. As refrigeration technology improved, and especially as electricity became cheaper through the twentieth century, commercial ice-making plants replaced imported ice. Finally, towards the end of the 20th century, the mass-produced commercial and domestic refrigerator arrived, killing off the ice trade, but contributing to the large increase in electricity consumption (see below).

Lighting

The past was very dark because artificial lighting was extremely expensive. This in turn was primarily due to the inefficiency of technology which depended on the naked flame. The basic process was one of combustion of a fuel, be it candle wax, lamp oil, or coal gas, so that the particles of soot in the flame glowed and gave off a tolerable light. Perceived light intensity is measured in *lumens*. A modern hundred-watt filament lamp emits about 1400 lumens, whereas a wax candle only emits about 13 lumens. A lumen is actually a unit of light energy, but one which uses the human eye as the meter. 'What is the brightness of a light?' may sound as vague a question as 'how long is a piece of string?' but by careful research it has been pinned down to an 'average' response of a large number of individuals. From this it has been possible to lay down standards of acceptable levels of illumination.

A reasonable modern standard for desk lighting is about 300 lumens per square metre, which would translate into 23 candles per square metre of desk surface! You may like to try reading this book by the light of a single candle to appreciate the problem. But in the past you might not have been able to afford more than this. For example a budget study of a 1760s Berkshire family estimated that they would have spent nearly 1% of their annual income to get a mere 28 000 lumen-hours of light (see Nordhaus, 1997). Put another way that is equivalent to two candles (and probably rather smelly tallow ones) for three hours per day!

Eighteenth and nineteenth century developments of oil and kerosene lamps managed to boost the output of a single lamp to 10 or 20 candlepower, but this was largely done by increasing the fuel throughput rather than the efficiency. It did not significantly improve the affordability of artificial light; nor did the introduction of lighting by town gas made from coal, which was priced to be competitive with oil and kerosene.

In the 1870s, electric arc lighting first appeared, but it was very harsh and bright and only really suitable for lighthouses and street lighting. Then in the 1880s the first commercial

Figure 3.7 A naked gas flame is an extremely inefficient light source (an example in Judge's Lodgings Museum, Presteigne)

incandescent electric lamps became available. These had the right lighting qualities to compete with oil and gas lamps. However, almost immediately the invention of the fabric gas mantle by Carl Auer von Welsbach improved the efficiency of gas lighting by a factor of four. This allowed it to compete with electric lighting well into the twentieth century (see Chapter 9). Since then there has been a continuous development both in new light sources and in the efficiency of electricity generation used to power electric lamps. The effectiveness of lights or lighting systems is expressed in terms of their **efficacy** (or 'usefulness') in lumens per watt. Table 3.1 below charts the progress over the years:

Table 3.1 Efficacy of different lighting sources

Lighting source	Approximate efficacy in lumens per watt
Candle	0.07
Gas mantle	0.9
Modern incandescent electric lamp	5*
Compact fluorescent lamp	25*
Low pressure sodium street lamp	60*

* Per watt delivered by the primary source, taking electricity generation efficiency as 33%

It is quite remarkable that the complex process of choosing to burn a litre of kerosene in an engine, to drive a generator, to power a fluorescent lamp, can produce 250–450 times more useful light than burning the same amount in an oil lamp. The overall result is that the real cost of useful light has fallen dramatically. It is thus not surprising that we now light our homes in a way that would have been impossible to afford in the past. The 1760s Berkshire family mentioned above spent 1% of their income to obtain 28 000 lumen-hours of light a year. Compare that with a sample 1960s US family who used over 13 000 000 lumen-hours per year for a paltry 0.3% of household income (Darmstadter, 1972).

Even so, it is worth reflecting that two billion people in developing countries do not have electric light and are effectively still technologically in the nineteenth century.

Industry

Physical labour

The word 'industry' normally conjures up pictures of smoking chimneys. However, it should not be forgotten that industry also includes a vast range of *physical* activities, digging, sawing, polishing, grinding, which are now carried out by machines.

The scene from the French workshop in Figure 3.8 shows labourers who are providing the physical work. They are likely to have kept this up for a whole working day, six days a week! Today their function would have been replaced by an 800 watt electric motor (about the rating of a heavy-duty DIY electric drill). Some tasks, such as endlessly sawing tree-trunks into planks or polishing flat sheets of glass by hand must have been mind-numbingly dull as well as physically exhausting.

The development of textile mills in Lancashire in the eighteenth century required mechanical energy to drive the spinning machines. The practical choices were: power from water mills, horses running in treadmills or the developing steam engines (see Chapter 6). By the 1840s it was clear that steam power was the way ahead and by the 1880s it was the normal source of motive power in UK factories.

But steam engines were heavy and difficult to move. They were ideal for ships, where weight was not a problem, but for motion on land they needed carefully laid rails with no steep gradients. By 1880, Victorian England was criss-crossed with railways on viaducts and cuttings, but all of this civil engineering construction work was done by the hand labour of a large army of 'navvies' (or navigators) and thousands of horses. The steam shovel, the bulldozer and the JCB digger are all twentieth century developments.

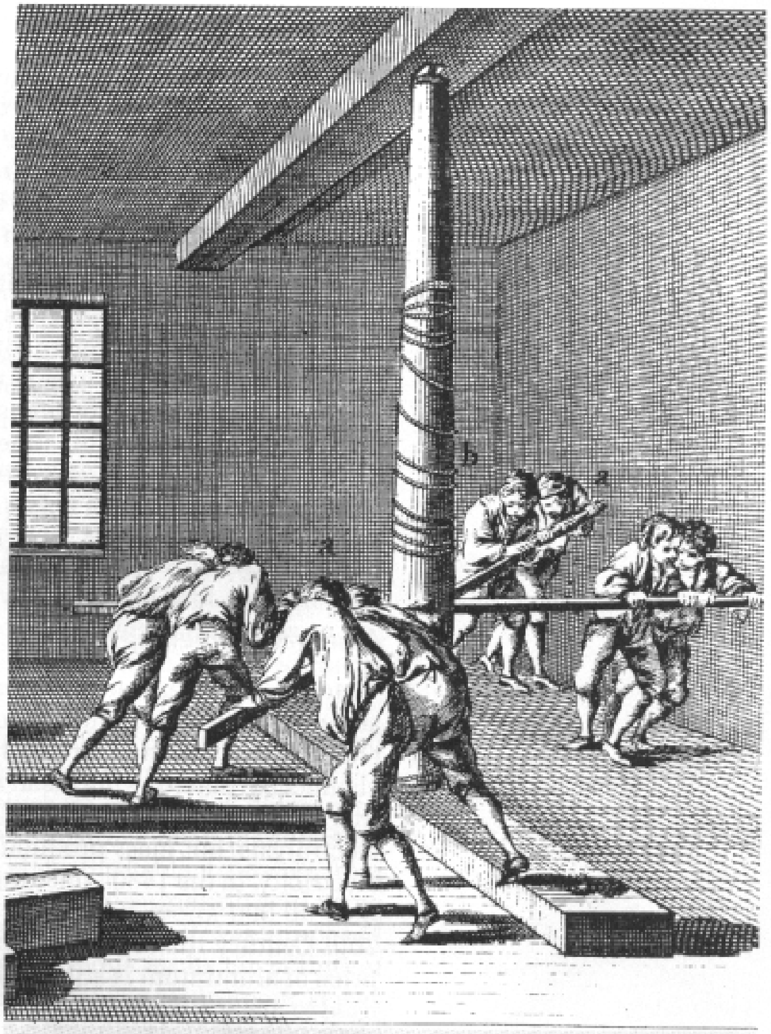

Figure 3.8 Eight men rotating a vertical capstan in a mid-eighteenth century French Workshop. The rope is pulling gold wire through a die (Diderot and D'Alembert (1769–1772))

Neither was the steam engine very suitable for small mechanical tasks. The domestic sewing machine, for example, was traditionally a hand or treadle-powered device. It had to wait until the twentieth century for the development of small, cheap, electric motors and the availability of cheap electricity to drive it. Now, it seems that almost everything has an electric motor in it. Even the average DIY tool box is now likely to contain an electric drill, an electric saw and probably even an electric screwdriver. All of this has contributed to the continuing rise in electricity demand (see below).

Iron and steel manufacture

The Europeans of 10 000 BC lived in the Stone Age. The Ancient Egyptians lived in the Bronze Age and we (from about 1000 BC onwards) live in the Iron Age. Extracting metals such as iron from their ores is not easy. It needs a fuel which is both capable of burning to produce a high temperature and chemically reacting with iron oxide to produce metallic iron. Traditionally this high quality fuel was charcoal – almost pure carbon made from wood. The charcoal-making process was not very efficient. It took about ten tonnes of wood to make one tonne of charcoal. In the UK the wood supplies held out until the seventeenth century when the switch to coal took place. Even then, the coal usually needed to be refined to coke to obtain the high temperatures (see Chapter 5).

Most early furnaces could not make pure iron. They produced a lumpy mixture of iron and slag which then had to be physically beaten out with hammers to produce 'wrought iron'. Thus eighteenth century iron foundries grew up where there were three resources – iron ore, coal, and water power to drive the bellows for the furnaces and the hammers. At that time it took ten tonnes of coke to produce one tonne of iron. Since then there have been continuous improvements in the processes beginning with the introduction of the blast furnace in the 1830s with steam engines to drive the bellows.

Wrought iron is not normally suitable for making tough machine components. For that you need steel which is made from iron by carefully burning off the carbon content. In Victorian Britain iron and steel production increased massively, swelling the energy needs of the 'production' sector. By 1903 it was using nearly 30 million tonnes of coal a year, over one-sixth of the country's total consumption. By this time it was possible to produce a tonne of iron with less than two tonnes of coke. Today, a century on, this figure has dropped to less than one tonne of coke per tonne of iron. However, in terms of total output, the UK iron and steel industry has now faded to a shadow of its former glory.

Aluminium smelting

Victorian steel was fine for steam engines, but not much use for 20th century aeroplanes, which required something much lighter. Aluminium as an element was isolated in 1824 but proved extremely difficult to purify chemically. Smelting the metal requires six times more energy than smelting iron. It was found that it could be separated from aluminium oxide using electrolysis, but mass production had to wait for the availability of cheap electricity. In the 1880s smelting 1 tonne of aluminium metal required more than 50 000 kilowatt-hours of electricity. Even though by the end of the 20th Century this figure had been reduced by more than two-thirds, the price of aluminium is still largely determined by the cost of the electricity used to make it. The 'embodied energy' of aluminium is amongst the highest of common household materials available today, which is why recycling of aluminium cans is an important energy-saving activity.

BOX 3.2 What is embodied energy?

Many materials require a large amount of energy to produce them. This is called their 'embodied energy'. It can be an important factor in choosing materials or even whole processes. Below are some example values.

Material	Energy Cost (MJ kg^{-1})	Production process
Aluminium	227-342	Metal from aluminium ore
Cement	5-9	From raw materials
Copper	60-125	Metal from copper ore
Plastics	60-120	From crude oil
Glass	18-35	From sand and other materials
Iron	20-25	From iron ore
Bricks	2-5	Baked from clay
Paper	25-50	From standing timber

Source: Smil, 1994

Processes that need high temperature heat

There are many other industries with a long history that need large amounts of high temperature heat. Brick making, for example, is simple enough, but requires enough energy to drive all the water out of what are essentially just lumps of mud. The other ingredients of traditional building practice are lime mortar and cement. The essential ingredient of lime mortar is quicklime or calcium oxide, made by heating chalk to drive off the carbon dioxide content. Cement is slightly more complex and is made by heating silicate clays to drive off the water content. The Romans used cement to build the 43 metre domed concrete roof of the Pantheon in Rome in 120 AD, but the secret of its manufacture disappeared and was only rediscovered in the nineteenth century. Its first major use in the UK was in the construction of the London sewers in the 1860s.

Glass making is another energy-intensive activity that has been practised for over 4000 years. It requires sufficient heat to melt sand. Traditionally this required a high quality fuel such as charcoal, or later coke, and a lot of hard work with the bellows to fan the flames. Since the whole point about glass is that it should be transparent, it is vital that the soot and grit from the fuel is kept out of the mixture. The ideal modern solution is to use electricity to provide the heat. As with aluminium the high embodied energy makes glass recycling important for energy saving.

In addition there are a whole host of other chemical processes that need process heat. One of the most important introduced in the early years of the nineteenth century was the manufacture of soaps and detergents, essential for the booming wool and cotton industries. Soap manufacture needed sodium hydroxide. This was produced by the Leblanc process from common salt (sodium chloride), limestone, coke and sulphuric acid using coal for process heat. Ironically, although the end product was supposed to be clean white textiles, this process was notorious for its air pollution consequences, emitting large quantities of hydrochloric acid vapour. It was this problem that led to the formation of the Alkali Inspectorate and some of the first UK legislation on industrial air pollution. Today, sodium hydroxide is made using electricity to separate the sodium and chlorine of common salt. Like aluminium smelting this is an industry that depends for its profits on cheap electricity.

If you look back at Figure 3.2 you will see that the total UK per capita energy use for industry in 2000 is little changed from 1880. This reflects the increased energy efficiency of production, but also a shift in the UK economy away from heavy energy-intensive industry to other high-value products such as electronics, and to earning more from the services sector (see below).

Transport

The modern growth in transport energy use is commented on at the end of this chapter, but it is worth pointing out that this can only occur because we are 'free' to travel. In many past societies (and some modern ones!) this was not an option. In the UK in 1300 AD feudal lords 'owned' the peasants as well as the farmland. They were every bit as tied to the land as the animals. Most people never travelled more than a day's walking distance from their homes in their whole lives. They were also limited by the atrocious state of the roads. The characters in Chaucer's Canterbury Tales were the lucky few - a pilgrimage to see Canterbury Cathedral was the closest they would get to a 'holiday'. The energy inputs to the transport sector were simple enough, wind power for sailing ships and copious quantities of hay and oats for horses.

By the 1880s society had changed entirely. People were, theoretically at least, free to do what they wanted and travel as they wished. Although road travel had improved during the eighteenth century, railways swept aside the expensive stage coach competition for long distance land travel. Steam ships were transporting freight not just on short coastal routes, but also on regular long-distance ocean-going routes. However, in the cities the horse bus and horse tram ruled the road. It was these and competing cheap railway fares that ushered in modern concepts of 'commuting' and 'suburbia'; it was no longer necessary to live next to your workplace. It was also permissible for the urban work force to have 'summer holidays' and they had the spare cash to afford them. The railway and steamship companies were only too happy to provide the transport arrangements to new seaside resorts. The transport energy sources were now still hay and oats for horses, but also enormous amounts of coal; by 1903 UK railways were using 13 million tonnes of coal a year and coastal shipping another 2 million tonnes. Photographs of the main roads at this time show them to be strangely empty by modern standards. Everything went by train and continued to do so well into the 20th century.

However, the urban horse did not last into the new century. In cities the electric tram and the petrol-engined bus had almost completely substituted for their horse equivalents by the First World War in 1914. This freed up large areas of hayfields around cities, which had provided the transport energy supply, for yet more suburbia and yet more commuting.

In the US, the motor car took off in 1907 with the famous Model 'T' Ford. Although Adolph Hitler introduced the Autobahn and his 'people's car', the Volkswagen, to Germany in the 1930s, the real explosion in car ownership in Europe did not come until after the Second World War. In the UK this was marked by the massive programme of motorway building in the 1960s and 70s. Although the growth in energy use for UK land-based transport flattened out in the late 1990s, that for international air transport, has continued to rise, encouraged by cheap air fares.

Services

If you live in a subsistence farming economy, as most people did until the 14th Century, your life style is very limited and most of the food and goods that you need are supplied locally. There is not much need for trade, distribution, or for that matter, money. By the time we reach the nineteenth century, England had become 'a nation of shopkeepers' as Napoleon put it. Farm produce had to be sold in cities and manufactured goods made in cities were traded world-wide. Distribution companies, banks and insurance companies became every bit as important as manufacturing industry, employing more and more clerks and increasing volumes of paper. In 1880 England, the 'Service sector' was limited but growing and it has continued to grow until the present day. Food and goods are things increasingly made by machines, while the sales, distribution and surrounding financial investment are activities done by people in offices and shops.

The Service sector includes almost all activities that aren't in the others. It includes all office activities in commercial offices and in public administration. It also includes education (and the writing of books such as this one). Educational expectations have increased enormously since the 1880s. The actual energy inputs to education are probably quite small – a recent study suggested that travel was the major energy cost of Open University courses, outweighing the energy costs of paper and printing (Roy *et al*, 2002).

'Services' also include newspapers and mass entertainment. In 1300 AD, there were no newspapers (Thomas Caxton only started printing books in the 1470s) and mass entertainment was limited to travelling story tellers. By 1880, Britain had high levels of literacy, a thriving newspaper and book publishing industry, all of which in turn depended on high volume paper manufacture, itself quite an energy-intensive industry. The development of radio and television in the 20th century has been a major spur to the spread of mains electricity from the 1930s onwards. It is not that the receivers actually require large amounts of energy; it is rather that the alternatives of battery power have always proved expensive and inconvenient.

Telecommunications is another important area in the services sector. By the 1880s the electric telegraph had been developed and criss-crossed Europe. There were even transatlantic cables. The telephone as we know it had just been invented. It is perhaps worth reflecting on how much useful communication the telephone and its modern descendent, the Internet, give for very little actual energy input.

Increasingly society is dependent on various electric and electronic devices for control and regulation. If the traffic lights fail in a modern city, then the result is grid-lock and chaos. But these are really only 'automatic traffic cops' substituting energy for a human presence. The early gas-lit version from the 1860s shown in Figure 3.9 still needed to be rotated manually. Whilst Victorian railways could physically propel 500 tonne trains at 100 kilometres per hour, they could only do so *safely* by the use of signalling, and this only became effective after the introduction of the electric telegraph in the 1850s. Similarly, modern airports can only function through the extensive use of radar and air traffic control. Given that in these examples so much can be achieved with such relatively small amounts of energy, it is perhaps amazing why we waste so much very crudely in other applications.

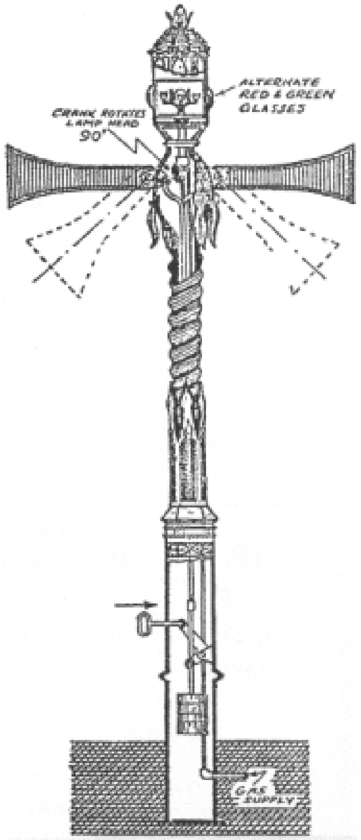

Figure 3.9 This early gas-lit traffic light, installed outside the Houses of Parliament, was described in the Times in 1868. The red and green lantern was rotated through 90° by a handle at the base, allowing it to control both traffic and pedestrians.

3.3 Energy uses today

The energy balance for the UK

By the end of the twentieth century, in the year 2000, total UK primary energy consumption had risen to almost 10 EJ, equivalent to almost a quarter of a billion tonnes of oil per year. The population had doubled from its 1880 figure to almost 60 million. Per capita annual primary energy use had risen to just over 165 GJ or almost 4 tonnes of oil equivalent. Whilst in the past the UK depended almost entirely on coal, 'diversity of supply' including oil, gas and nuclear power is now a key aim of energy policy.