Societies before the Industrial Revolution were dependent on the annual cycle of plant photosynthesis for both heat and mechanical energy. The quantity of energy available each year was therefore limited, and economic growth was necessarily constrained. In the Industrial Revolution, energy usage increased massively and output rose accordingly. The energy source continued to be plant photosynthesis, but accumulated over a geological age in the form of coal. This poses a problem for the future. Fossil fuels are a depleting stock, whereas in pre-industrial time the energy source, though limited, was renewed each year.

1. Introduction

Major changes in the material culture of societies, and in particular in their ability to sustain larger populations, have been closely associated with changes in the scale and type of energy available to meet human needs for nutrition and to perform work. Like all other animate life on the Earth, people were long dependent primarily upon plant photosynthesis as the ultimate source of the energy they consumed. Plant photosynthesis, by capturing a small fraction of the energy reaching the surface of the Earth in the form of insolation, provided the basis for all animate life, both for herbivores and, higher up the food chain, for carnivores. The annual amount of energy captured by plant photosynthesis, therefore, represented an upper limit to the energy available for any productive activity by human groups. All societies before the Industrial Revolution were subject to this overall constraint, but even in the period before the Industrial Revolution, there were major changes in scale of energy that was secured for human use. As a background to describing the fundamental change that occurred in the Industrial
Revolution, it may be helpful to briefly describe the course of change during the long period when the annual round of plant growth secured by photosynthesis remained almost the sole energy source.

Initially people competed with other animals for the natural products of the environment in which they lived, and in doing so depended essentially on their muscular strength. The first major change in the energy at man’s disposal came with the discovery of methods to generate and to control fire. Plant photosynthesis had provided food, which both sustained life and made available mechanical energy in the form of human muscle. The control of fire gave access to heat energy. By providing warmth in cold seasons, fire increased the geographical range of human settlement, but perhaps more importantly the development of cooking substantially increased the range of food available for consumption, while at the same time reducing the energy needed to digest it. In parallel, the use of fire made it possible to smelt metal ores. Tin, copper and iron tools allowed the development of new crafts and the further refinement of existing crafts: furthermore, metal weapons changed the balance of power between man and other predators. Deliberate and controlled firing of plant cover could also be used to modify the local vegetation cover for human benefit. It is no accident that fire held great symbolic significance in many early religions: the duty of the priesthood often involved the indefinite preservation of a holy flame [1].

A second and more radical change in the quantity of energy available for human use took place during the Neolithic food revolution with the development of settled agriculture. Immense areas of fertile land were cleared of their natural vegetation and used exclusively to grow crops for human consumption or to provide fodder for farm animals. Instead of competing with other animals for edible plants and with local predators for the grazing animals that could provide meat, the whole product of enormous tracts of land was reserved exclusively for human use. Populations were able to expand by an order of magnitude. Large permanent settlements became possible; urban societies developed. Political, military and religious elites emerged and created complex administrative structures. There were parallel cultural changes, notably the development of writing, with its profound importance for many aspects of individual and community life.

The changes that took place in the wake of the Neolithic food revolution were immense, but the bulk of the population remained poor by standards that have since become normal in industrialized societies. The opportunities for economic growth in pre-industrial societies remained severely constrained by energy supply. The quantity of energy reaching the surface of the Earth from the Sun each year is huge, but plant photosynthesis characteristically captures only between 0.1 and 0.4 per cent of this total. As an example, the energy brought by insolation to the surface of Britain each year has been estimated as equivalent to the energy contained in 20 billion tonnes of coal, but because of the limited capture of this total inherent to the nature of plant photosynthesis, the maximum energy that could be secured by an economy subject to this restriction sets severe limits to productive possibilities [2, pp. 2, 12; 3, p. 2]. One-tenth of 1 per cent of 20 billions is only 20 million tonnes, approximately one-fifteenth of the coal-equivalent energy use figure in Britain today.

2. Organic economies

All economies before the Industrial Revolution may be described as organic economies; organic because they operated under the constraints imposed by the annual amount of insolation and the process of photosynthesis in plants. In organic economies, the growth horizon was limited because the scale of energy supply that was accessible represented a severe constraint upon prolonged growth.

Those living in organic economies were well aware of the limitations associated with organic economies. A poor harvest, for example, was the signal for a difficult year ahead. If the harvest was sufficiently bad, the poorest sections of the population might well face severe malnutrition, even starvation. In considering the nature of organic economies, it is illuminating to consider the views of the classical economists: they displayed a clear understanding of their nature. They were
writing in the period often designated as the era of the Industrial Revolution, the last decades of
the eighteenth century and the opening decades of the nineteenth, but their views were formed by
their understanding of the world before it began to be transformed by the Industrial Revolution. Despite their advocacy of the benefits of a market economy in promoting growth and increasing
the efficiency with which capital and labour were employed, Adam Smith, David Ricardo and
Thomas Malthus (the three most eminent of the classical economists) were adamant that growth
must be limited and that the end state following a period of growth might well be as miserable
as the situation prevailing at its beginning [4]. They used a different explanatory framework to
bring home the problem that I have described in terms of energy. They focused on the fact that
the area of land suitable for farming use was limited and could not be significantly increased.

The classical economists identified three basic requirements for production to take place: it
must involve capital, labour and land. Supplies of the first two factors of production could, in
principle, be extended indefinitely, but the supply of land was fixed by the geography of the
globe. All the food and virtually all the raw materials used in material production were produced
by agriculture. The scale of any potential increase in the supply of wool, leather, wood and a
host of similar raw materials was necessarily limited by the productivity of the land. Equally, the
output of metals was similarly limited, as it required an abundant supply of heat to smelt mineral
ores, and wood and charcoal were the source of the heat in question. If any form of material
production was to be increased, more production must be secured from the land. Yet, since the
most productive land was settled first, this meant either taking into cultivation land of inferior
quality or using existing land more intensively, or some combination of the two. This in turn
implied decreasing returns to capital and labour. At some point, growth would therefore come
to a halt. The very nature of growth, because it involved achieving an increased output from the
land, a production factor that could not be expanded to match, ensured that it must first decelerate
and later cease. As Smith remarked [5, I, p. 106]:

In a country which had acquired that full complement of riches which the nature of its soil
and climate, and its situation with respect to other countries, allowed it to acquire; which
could, therefore, advance no further, and which was not going backwards, both the wages
of labour and the profits of stock would probably be very low.

Reviewing the same problem 40 years later Ricardo came to the same gloomy conclusion, adding
that ‘This [a state of affairs in which both capital and labour would enjoy very poor returns]
will necessarily be rendered permanent by the laws of nature, which have limited the productive
powers of the land’ [6, pp. 125–126].

Malthus supplied an additional consideration, which reinforced the gloomy conclusion to be
drawn from the nature of all organic economies. Drawing upon the knowledge acquired as an
undergraduate in Cambridge studying mathematics, he made use of the distinction between the
nature of arithmetic and geometric progressions. He suggested that, even on the most optimistic
of assumptions, output from the land could not be expected to rise faster than in arithmetic
progression. Population, on the other hand, unless checked, would rise in geometric progression.
At some point, this must cause pressure on living standards, as numbers approached a ceiling
set by land productivity, with depressing implications for living standards [7, pp. 8–10]. Growth,
therefore, in the eyes of the classical economists, was necessarily asymptotic. The very nature of
the growth process resulted in due course in its deceleration and eventual cessation. The modern
conviction that economic growth is normally exponential would have been regarded as somewhat
fantastic to those living in organic economies. It is therefore not surprising that it took time for
the nature of the new age to become apparent to contemporaries.

It is testimony to the difficulty that contemporaries experienced in recognizing the implications
of the changes in train during the Industrial Revolution that, as late as the middle decades of the
nineteenth century, John Stuart Mill [8, I, p. 182], in re-examining the issue of sustained growth,
felt that the pessimism of the classical economists was justified, though recognizing that it was
conceivable that the traditional barriers to growth might be overcome. It was not until the final third of the nineteenth century that the nature of the new world that had come into existence was widely appreciated, and the term ‘Industrial Revolution’ became widely used. Karl Marx’s anger at the capitalist system stemmed from a recognition that a new era had begun, that exponential growth was taking place but that the benefit of the new ability to create wealth was benefiting only a tiny minority.

In the event, the pessimism of the classical economists proved unfounded, though their logic was impeccable. They analysed the problem in relation to the fixed supply of land. I have done the same while expressing the problem in energy terms. This is convenient because it points to the change that provided an escape from the constraints that had previously limited growth. Production in organic economies was limited by the supply of energy captured by the annual cycle of plant photosynthesis. Paradoxically, plant photosynthesis continued to be the dominant source of energy in the new era, conventionally termed the Industrial Revolution, but it was the energy drawn from many millions of years of plant photosynthesis in the form of coal, rather than the limited product of a single year, that had for so long set the ceiling to energy availability. At much the same time as Marx advanced one view of the new situation brought about by the Industrial Revolution, William Jevons [9, p. 2] wrote extensively about what he termed ‘the coal question’. He was in no doubt that it was the use of coal that had ended what he termed the ‘laborious poverty of early times’.

3. The significance of exploiting a new source of energy

Given the nature of organic economies, indeed, it might be argued that the key question regarding the Industrial Revolution is not how it first gathered momentum but why it did not grind to a halt in the manner forecast by the classical economists. Periods of increasing prosperity and economic sophistication had occurred previously but had lost rather than gained momentum because pressure on the land inevitably increased as production rose. When Sir Thomas More in Tudor times complained that the sheep were eating up the men, he was drawing attention in a thought-provoking manner to the inescapable problems of organic economies. He wrote ‘your sheep that were wont to be so meek and tame and so small eaters, now, as I hear say, be become so great devourers and so wild, that they eat up and swallow down the very men themselves’ [10, p. 26]. If the woollen industry was flourishing and the demand for wool therefore rising, more land might be devoted to sheep pasture, but this must mean less land available to grow corn for human consumption, or less land under forest, which must at some point create difficulties for the production of charcoal for iron production. It is simple to demonstrate how seriously dependence upon the produce of the land limited output. Iron and steel were critical to the progress made during the Industrial Revolution, yet if half the land surface of Britain had been covered with woodland, it would only have sufficed to produce the charcoal needed to smelt perhaps $1\frac{1}{4}$ million tonnes of bar iron on a sustained yield basis [11, p. 16]. The creation of a national rail network, for example, would have been physically impossible without the transition to fossil fuels as the principal energy source because of the quantity of iron and steel needed for rails, engines and rolling stock.

To make the same point in a different way, one might say that, to make it possible for an industrial revolution to take place, not one but two capitalisms were needed. The development of a market economy, a capitalist economy, such as that achieved in The Netherlands in their ‘golden age’ in the seventeenth century, can give rise to higher levels of output per head but cannot in itself produce an industrial revolution. For that to occur, a second kind of capital proved necessary. Gaining access to a capital stock of energy built up over a geological era was also essential, since it meant that energy could be expended on a scale that was not otherwise available.

Mediaeval philosophers distinguished between what they termed fungibles and consumptibles. A field was fungible because its use in any one year did not prevent using it for the same purpose in the next. A loaf of bread was a consumptible, because after it had been consumed its use was ended. This distinction clarifies an important difference between organic economies and an
economy based on fossil fuels, which emerged first in Britain. The supply of energy in organic economies was fungible in nature. The use of the product of plant photosynthesis in any one year did not affect its availability in the following year. Fossil fuels, in contrast, are consumptibles. Each tonne of coal burnt slightly reduces the stock left to be burnt in the future. Unless industrial societies can find ways of returning to dependence on fungible sources of energy, in the long run they will face very serious, even disastrous, problems, whose nature is quite different from the problems faced by organic societies in the past.

4. The contrast between England and continental Europe

In recent years, it has become possible to track the changing balance of the several major sources of energy in a number of European countries because of the work of a group of like-minded scholars. They agreed on a common method of measurement and common definitions of energy sources. In the case of England, this can be done from the sixteenth century onwards. I turn now, therefore, to a description of the course of change in energy supply in England over a period of more than three centuries. Table 1 summarizes the course of change over these three centuries. Energy consumption increased in absolute terms in all the categories employed, with the exception of firewood. The increases were substantial in all the other categories, but, whereas coal was a minor player in the mid-sixteenth century compared with draught animals, firewood and people, by the mid-nineteenth century it dwarfed all the other categories combined.

Table 2 drives home this point by listing the percentage share of each energy source in each period. Coal supplied only one-tenth of all the energy consumed at the beginning of the period but by its end it accounted for nine-tenths. The only other energy source to increase its percentage share over the three centuries was wind power. This reflects principally the great expansion in the number and size of sailing vessels from the seventeenth century onwards. Windmills played only a minor role.

Table 3 depicts the same changes by showing the annual consumption of energy per head of population. Population grew so substantially over the three hundred year period that, despite the marked growth in the absolute scale of energy consumption, consumption per head increased only in the case of wind power and coal. The outstanding feature of all three tables is unquestionably the immense increase in the importance of coal as an energy source.

In considering the data shown in the tables, it should be noted that the energy consumption data reflect not work performed but raw consumption. For example, the totals for human and draught animal consumption represent food and fodder consumption. In both cases, a substantial proportion of the consumption was used for bodily maintenance, leaving only a balance that could be applied for useful work. Or again, only a tiny fraction of the energy released in burning coal was harnessed successfully to perform work in the eighteenth century.

Figure 1 repeats the information given in table 3 in the form of a graph showing both the phasing of the rise of coal and its increasing dominance of the energy picture from the end of the seventeenth century onwards. The figure also suggests how distinctive England was. The per capita data for Italy in the 1860s are closely similar to the data for England three centuries earlier. Energy derived from burning wood was relatively more important in Italy and that afforded by draught animals figured more prominently in England, a contrast that is not surprising given the different geography of the two countries, but the overall picture in the two countries is similar. Preliminary estimates for other European countries in the late eighteenth and early nineteenth centuries suggest that the level of energy consumption per head found in Italy in the 1860s was broadly true of other European countries until the beginning of the nineteenth century, with the important exception of The Netherlands, where the stored product of plant photosynthesis in the form of peat played a part in facilitating its success in the Dutch ‘golden age’ in the seventeenth century.

1 The initiative in this venture was taken by Prof. Astrid Kander of the University of Lund and Dr Paul Warde of the University of East Anglia.
of the capital could be met without experiencing the rising marginal cost that would have been
the Tyne valley and that transport by sea was relatively cheap meant that the domestic fuel needs
[15, table 4.1, p. 68 and table 14.2, p. 497]. The fact that coal outcropped close to the surface along
A substantial part of the growth in national coal output was the result of the growth of London
each half-century. During the seventeenth century, much of the coal was burnt domestically .
expanded steadily. Over the whole period, it rose 13-fold. On average, it roughly doubled in
Wales was assumed to be 7% of the English total.

Table 1. Annual energy consumption in England and Wales, 1561–1570 to 1850–1859 (terajoules).

<table>
<thead>
<tr>
<th>Year</th>
<th>human</th>
<th>draught animals</th>
<th>firewood</th>
<th>wind</th>
<th>water</th>
<th>coal</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1561–1570</td>
<td>14860</td>
<td>21100</td>
<td>21490</td>
<td>200</td>
<td>550</td>
<td>6930</td>
<td>65130</td>
</tr>
<tr>
<td>1600–1609</td>
<td>19190</td>
<td>21430</td>
<td>21810</td>
<td>390</td>
<td>700</td>
<td>14540</td>
<td>78060</td>
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<td>1650–1659</td>
<td>26080</td>
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<td>22200</td>
<td>880</td>
<td>900</td>
<td>39060</td>
<td>116820</td>
</tr>
<tr>
<td>1700–1709</td>
<td>27330</td>
<td>32780</td>
<td>22480</td>
<td>1360</td>
<td>990</td>
<td>84000</td>
<td>168940</td>
</tr>
<tr>
<td>1750–1759</td>
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<td>22560</td>
<td>2810</td>
<td>1300</td>
<td>140810</td>
<td>230850</td>
</tr>
<tr>
<td>1800–1809</td>
<td>41810</td>
<td>34290</td>
<td>18540</td>
<td>12660</td>
<td>1100</td>
<td>408680</td>
<td>517080</td>
</tr>
<tr>
<td>1850–1859</td>
<td>67800</td>
<td>50090</td>
<td>2240</td>
<td>24360</td>
<td>1700</td>
<td>168910</td>
<td>1835300</td>
</tr>
</tbody>
</table>

Table 2. Percentage share of each energy source.

<table>
<thead>
<tr>
<th>Year</th>
<th>human</th>
<th>draught animals</th>
<th>firewood</th>
<th>wind</th>
<th>water</th>
<th>coal</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1561–1570</td>
<td>22.8</td>
<td>32.4</td>
<td>33.0</td>
<td>0.3</td>
<td>0.8</td>
<td>10.6</td>
<td>100</td>
</tr>
<tr>
<td>1600–1609</td>
<td>24.6</td>
<td>27.5</td>
<td>27.9</td>
<td>0.5</td>
<td>0.9</td>
<td>18.6</td>
<td>100</td>
</tr>
<tr>
<td>1650–1659</td>
<td>22.3</td>
<td>23.7</td>
<td>19.0</td>
<td>0.8</td>
<td>0.8</td>
<td>33.4</td>
<td>100</td>
</tr>
<tr>
<td>1700–1709</td>
<td>16.2</td>
<td>19.4</td>
<td>13.3</td>
<td>0.8</td>
<td>0.6</td>
<td>49.7</td>
<td>100</td>
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<tr>
<td>1750–1759</td>
<td>12.9</td>
<td>14.6</td>
<td>9.8</td>
<td>1.2</td>
<td>0.6</td>
<td>61.0</td>
<td>100</td>
</tr>
<tr>
<td>1800–1809</td>
<td>8.1</td>
<td>6.6</td>
<td>3.6</td>
<td>2.4</td>
<td>0.2</td>
<td>79.0</td>
<td>100</td>
</tr>
<tr>
<td>1850–1859</td>
<td>3.7</td>
<td>2.7</td>
<td>0.1</td>
<td>1.3</td>
<td>0.1</td>
<td>92.0</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3. Annual energy consumption per head of population (megajoules).

<table>
<thead>
<tr>
<th>Year</th>
<th>human</th>
<th>draught animals</th>
<th>firewood</th>
<th>wind</th>
<th>water</th>
<th>coal</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1561–1570</td>
<td>4373</td>
<td>6210</td>
<td>6324</td>
<td>59</td>
<td>162</td>
<td>2039</td>
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<td>4161</td>
<td>4647</td>
<td>4729</td>
<td>85</td>
<td>152</td>
<td>3153</td>
<td>16925</td>
</tr>
<tr>
<td>1650–1659</td>
<td>4521</td>
<td>4802</td>
<td>3849</td>
<td>153</td>
<td>156</td>
<td>6772</td>
<td>20253</td>
</tr>
<tr>
<td>1700–1709</td>
<td>4789</td>
<td>5744</td>
<td>3939</td>
<td>238</td>
<td>173</td>
<td>14719</td>
<td>29602</td>
</tr>
<tr>
<td>1750–1759</td>
<td>4519</td>
<td>5113</td>
<td>3429</td>
<td>427</td>
<td>198</td>
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<td>1850–1859</td>
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<td>2633</td>
<td>118</td>
<td>1280</td>
<td>89</td>
<td>88779</td>
<td>96462</td>
</tr>
</tbody>
</table>

Source: [12, appendix 1, tables 1, 2, and 3, pp. 115–136]. Population totals for England from [13, table A9.1, pp. 614–615]. The population of Wales was assumed to be 7% of the English total.

century. As late as the middle of that century the per capita quantity of energy in The Netherlands
derived from peat was roughly twice as large as the comparable figure in England from coal
[11, p. 221].
Throughout the period from the 1650s to the 1850s coal consumption per head in England expanded steadily. Over the whole period, it rose 13-fold. On average, it roughly doubled in each half-century. During the seventeenth century, much of the coal was burnt domestically. A substantial part of the growth in national coal output was the result of the growth of London [15, table 4.1, p. 68 and table 14.2, p. 497]. The fact that coal outcropped close to the surface along the Tyne valley and that transport by sea was relatively cheap meant that the domestic fuel needs of the capital could be met without experiencing the rising marginal cost that would have been
inevitable if wood had been the main source of fuel. By the later seventeenth century, as much as half of the tonnage of the English mercantile marine probably consisted of ships moving coal from the Tyne to the Thames [16, I, pp. 239–240]. London grew rapidly during the later sixteenth and seventeenth centuries. In ca 1500, London was not among the 10 largest cities in Europe; by 1700, it was the largest, with half a million inhabitants [17, appendix 1, pp. 269–278]. To have met the fuel needs of London from woodland would have meant taking the annual growth of timber from an area of perhaps 1250 square miles by 1700 and would have required a large number of horses to transport the wood to market [11, p. 40]. This transport requirement would have added substantially to the area of land needed to service the capital’s fuel needs (i.e. land for pasture and for the cultivation of oats would have been needed in addition to the woodland). As London grew, the pressure exerted by economic growth on available land, the problem that haunted the classical economists in their discussion of growth possibilities, could be avoided by substituting coal for plant growth.

5. Heat energy and mechanical energy

Coal was also increasingly used for industrial processes. Substituting coal for wood as a source of heat was straightforward in many industries, such as salt boiling or brewing, where the source of heat was separated from the material being heated by a metal barrier. Where this was not the case, as in the smelting of ores, chemical impurities in the coal might be transmitted to the material being heated. This explains the prolonged difficulties in the successful smelting of iron using coal or coke.

The larger the amount of heat needed to effect an industrial operation, the greater the incentive to replace wood by coal and the larger the potential reduction in production costs. The use of coal made it possible to turn brick into the prime building material in early modern England. The manufacture of glass also required much heat energy. English travellers on the continent in the eighteenth century were struck by the rarity of window glass in the villages and towns that they visited. Arthur Young [18, p. 22] frequently commented on this: ‘Pass an extraordinary spectacle for English eyes’, he wrote, ‘of many houses too good to be called cottages, without any glass windows’. Abundant coal meant cheaper glass.
Broadly speaking, coal could be substituted as a source of heat energy for all the purposes where wood had once been used, though sometimes only after a long period of trial and error. But this success would not in itself have overcome the barrier to exponential growth that had affected all organic economies. It solved the problem of enlarging the supply of heat energy, but mechanical energy remained a problem. Mechanical energy and heat energy had long been regarded as distinct categories. There was therefore no apparent reason why overcoming the problem of energy supply in one of these two categories should hold out hope of solving the other. Mechanical energy was needed in all agricultural, manufacturing and transport activities and had always been provided dominantly by the muscle power of men and draught animals. Wind and water power were only of minor importance (table 1). Hence the immense significance of the gradual development of the steam engine. This proved to be of critical importance in enabling the whole range of energy supply problems to be solved because it enabled heat energy to be transformed into mechanical energy. Émile Levasseur, writing towards the end of the nineteenth century, epitomized the importance of the steam engine vividly. Noting that one steam horse power was estimated as providing the power equivalent of 21 manual labourers, he suggested that in France ca 1840 steam engines were performing the work of 1.2 million labourers but that by the mid-1880s the rapid expansion in the use of steam engines meant that this figure had risen to 98 million labourers, ‘two-and-a-half slaves for each inhabitant of France’ [19, III, p. 74].

The history of the development of the steam engine was itself closely bound up with the increasing scale of coal production. The traditional method of evacuating water from the mine had relied on wind power or the muscle power of horses. In general, this meant that it was not possible to sink a mine more than about 150 feet underground, since below that depth the mine would flood [20, p. 114]. The first solution to the problem involving fossil fuel was the development of the Newcomen engine. It relied upon the power created by causing a vacuum rather than making direct use of the expansive power of steam, and it was extremely inefficient. Only a tiny fraction of the energy released by burning coal was effectively harnessed (about 0.5% [21, p. 67]). Coal was bulky, heavy and therefore expensive to transport. With the Newcomen engine the output of coal could be increased, since mine shafts could be driven deeper yet kept free from flooding, but because the cost of coal rose steeply with distance, the Newcomen engine remained largely confined to use at the pithead. It could not be operated economically at any distance from a mine. The early steam engines of James Watt were less inefficient and their use was less geographically constrained, but further advances in efficiency were needed to make the steam engine a general-purpose source of mechanical energy. It took a further half-century of development during which the efficiency of the steam engine was greatly enhanced to turn it into a workhorse of general application throughout industry.

It is ironic that, although the use of coal was instrumental in overcoming the constraints to growth that had long left the bulk of all populations in poverty, both making possible a steady increase in output per head and raising living standards, coal production itself remained a matter of hard physical effort by individual miners. Output per head in the coal industry changed little over the centuries surveyed in this paper. But the amount of energy contained in the coal dug by each miner was massively greater than the energy generated from other sources in the course of a working day. Fred Cottrell illustrated the point in a vivid manner, even though his illustration relates to the very early days of the steam engine [22, p. 86]:

A coal miner who consumes in his own body about 3,500 Calories a day will, if he mines 500 pounds of coal, produce coal with a heat value 500 times the heat value of the food which he consumed while mining it. At 20 per cent efficiency he expends about 1 horsepower-hour of mechanical energy to get the coal. Now, if the coal he mines is burned in a steam engine of even 1 per cent efficiency it will yield about 27 horsepower-hours of mechanical energy. The surplus of mechanical energy gained would thus be 26 horsepower-hours, or the equivalent of 26 man-days per man-day. A coal miner, who consumed about \( \frac{1}{3} \) as much food as a horse, could thus deliver through the steam engine about 4 times the mechanical energy which the average horse in Watt’s day was found to deliver.
Placed at the disposal of workers in an iron foundry in the form of heat, or providing vastly greater power for each man or woman supervising the operation of looms in a cotton factory, the use of coal as an energy source made possible a dramatic rise in productivity per worker. Jevons was justified in regarding the use of coal as making it possible to overcome what he termed the 'laborious poverty' of earlier times. The part played by coal as the source of cheap and abundant energy in creating a distinctive path to sustained growth and rising living standards has been emphasized recently by Allen [23, ch. 4].

The advantages of access to a supply of cheap and abundant energy, which, in stark contrast with organic economies, could be expanded at will, carried Britain to a peak of relative economic success in the middle of the nineteenth century, symbolized by the remarkable impact of the Great Exhibition of 1851. The advantage enjoyed by Britain because of its pioneering use of coal may be briefly illustrated. In the quinquennium 1850–1854, the three largest continental coal producers were Belgium, France and Germany, with a combined average annual output of 18.6 million tonnes. The equivalent figure for Britain was 58.0 million tonnes in the same period. Expressed per head of population, the contrast was even more striking. The figure for the three continental countries combined was ca 0.24 tonnes per person each year; the comparable figure for England and Wales was 2.87 tonnes [24, table E2, pp. 381–391]. Nor was the contrast in output levels confined to coal production. In the same quinquennium, the average annual production of pig iron in Belgium, France and Germany combined was 1.1 million tonnes: the equivalent figure for Britain was 2.9 million tonnes. Raw cotton consumption in the three continental countries combined over the same period averaged 104 000 tonnes; the British figure was 319 000 tonnes [24, table E8, pp. 412–419 and table E14, pp. 448–454].

6. Conclusion

Growth in all organic economies tended to be asymptotic. As output rose, a point was always reached where the marginal cost of producing goods began to rise, in due course arresting further growth. It had seemed impossible to escape from this constraint. Hence it was always difficult, sometimes virtually impossible, for contemporaries to grasp the significance of the entirely novel developments in which they were caught up. A quotation from The wealth of nations, arguably the most influential work of economics ever published, illustrates this point. Adam Smith remarked ‘all over Great Britain manufacturers have confined themselves to the coal countries’. He ascribed the location of manufacturing industries on coalfields to the fact that in countries with cold winters fuel was ‘a necessary of life, not only for the purpose of dressing victuals, but for the comfortable subsistence of many different sorts of workmen who work within doors’. Coal was the cheapest fuel and ‘The price of fuel has so important an influence on that of labour, that other areas could not produce as cheaply as on the coalfields because high fuel prices mean high labour costs’ [5, II, p. 404]. Smith did make reference to coal as a ‘necessary instrument of trade’ in the iron, glass and metal industries, and he was writing in the 1770s, in the early decades of the Industrial Revolution, when the transformation that it brought about still left much manufacturing little changed, but his remarks neatly illustrate the difficulty of identifying the significance of the changes then in train.

With the benefit of hindsight the significance of the new energy source is much easier to appreciate. Over the period from the mid-sixteenth to the mid-nineteenth century, Britain pioneered a route into a radically different type of economy from any that preceded it. In focusing on only one aspect of a vastly complex series of interlocking changes that made this possible, I am neglecting many topics that would demand extensive treatment in a fuller description and analysis of the Industrial Revolution. What can, however, be asserted with confidence is that a necessary condition for the move from a world where growth was at best asymptotic to one in that it could be, at least for a period, exponential was dependent upon the discovery and exploitation of a vast reservoir of energy that had remained untapped in organic economies.
Only by adding the products of plant photosynthesis accumulated over a geological age to the annual cycle of photosynthesis, which had previously been the source of almost all the energy available for human use, could the energy barrier that had constrained growth so severely in the past be overcome.

References

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