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Excerpt
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Introduction

The object of this book is to describe the transformation in the capacity to produce goods and services which took place in England over a period of three centuries between the reigns of Elizabeth I and Victoria, and which is conventionally termed the industrial revolution. At the beginning of the period England was not one of the leading European economies. It was a deeply rural country where agricultural production was largely focused on local self-sufficiency. In part this was a function of the low level of urbanisation at the time. England was one of the least urbanised of European countries: the only large town was London. The market for any agricultural surplus was limited other than close to the capital city. There was therefore little inducement to undertake improvement. Industry was little developed compared with the situation in the more advanced continental countries. Across a wide range of products there was little or no domestic production.[1] When an initiative was taken to create a domestic source of supply, it was often the case that foreign expertise was sought to enhance the chances of success. England was on the periphery of Europe economically as well as geographically. However, although other European economies were well in advance of England in the mid sixteenth century, all were subject to the limits to growth that were common to all organic economies.

The underlying constraint that prevented sustained growth in organic economies arose from the nature of its energy sources. All acts of material production, whether in the field, the forest, the workshop, or the household necessarily involved the expenditure of energy; and the same was true of all types of transport. But the quantum of energy that could be secured for these purposes was limited. It was based almost exclusively on the energy secured by the process of plant photosynthesis. The conversion of raw materials into finished products always involved the expenditure of either mechanical or heat energy, or both. The great bulk of the mechanical energy was provided by human or animal muscle power. This

[1] See pp. 86–8.

energy came from plant photosynthesis in the form of food or fodder. Wind and water power was of relatively slight importance.[2] Heat energy was secured from burning wood or charcoal. This too, therefore, was the product of plant photosynthesis. Most of the raw materials used by industry in organic economies were also vegetable, such as wood, wool, cotton, or leather. Even when the raw material was mineral, plant photosynthesis was essential to production, since converting ores into metals required a large expenditure of heat energy that came from burning wood or charcoal. When smelting iron or baking bricks no less than when operating a loom to produce woollen cloth or ploughing a field to prepare for next year's harvest, the energy involved was derived from plant photosynthesis. Directly or indirectly, therefore, almost all forms of material production depended on access to the energy available from this source.

The energy reaching the surface of the earth each year far exceeds the quantity of energy used by human societies even today, but plant photosynthesis captures only a very small fraction of such energy, and organic economies were constrained in what they could produce and transport by the degree of success they achieved in tapping this energy source. For reasons which are described in later chapters, the very nature of growth in organic economies at some stage necessarily involved rising costs per unit produced and falling output per head, a point familiar to the classical economists. They used a different framework of analysis to that used in this book, but came to the same conclusions about the constraints upon prolonged growth.

It is critical to the understanding of the difference between organic economies and those transformed by an industrial revolution that the energy available to organic economies was a *flow* from the sun whose scale scarcely varied from one year to the next. The quantity captured by a community might be increased if technical advance and invention made it possible to secure a larger fraction of this energy flow, but only within a ceiling set by the scale of plant photosynthesis. Small increases in the efficiency of energy capture for human use occurred from time to time and were cumulatively substantial. Occasionally, as in the era of the neolithic food revolution, a major advance in energy capture might lead to profound economic and social change, but the ceiling jointly set by the nature of plant photosynthesis and the productive technology of any given society prohibited prolonged economic growth.

The industrial revolution depended on securing access to vastly greater energy supplies. The energy required to produce, say, iron and steel on a large scale or to construct and operate a railway system implied that it

[2] See Table 3.2, p. 34.

was idle to expect that it could be secured from the annual *flow* of energy derived from plant photosynthesis. The possibility of bringing about an industrial revolution depended on gaining access to a different source of energy. Mining coal provided the solution to this problem. It enabled societies to escape from what Jevons termed 'the laborious poverty of early times'.[3] Coal consumption roughly doubled in each half-century between the reigns of Elizabeth and Victoria. Coal, however, is a *stock* not a *flow*. Each ton of coal dug from a mine marginally reduces the size of the stock, and the same is true of all fossil fuels. Since drawing upon a stock will ultimately lead to its exhaustion, the use of fossil fuels creates problems not faced when the energy source is a flow. In the long term, dependence on an energy stock is perilous, but there can be no doubt of the benefits that can follow from exploiting a stock of fossil fuel in the short term. It makes possible the attainment of a scale of production that is otherwise beyond reach.

This book shares an underlying theme with an earlier publication, *Energy and the English industrial revolution*, in stressing the importance of exploiting fossil fuel as a new energy source, but its scope is wider, covering many topics which did not figure in the earlier work, as may be inferred from the description of chapters which follows.

The first chapter defines the exceptional character of the industrial revolution by contrasting it with two earlier transformations of organic economies that are often compared to the industrial revolution; the conquest of fire and the neolithic food revolution. This helps to make apparent the sense in which the industrial revolution involved more radical change than anything that preceded it. Next, Chapter 2 describes the analysis of the character of organic economies made by the classical economists since this, too, is instructive as background to an appreciation of the nature of an industrial revolution.

There follows a group of chapters (Chapters 3–5) which describe the interplay between advances in the traditional forms of production and those arising from the increasing consumption of coal in production processes; in other words, the blending of growth which is possible within the constraints of an organic economy with the growth made possible by tapping a new energy source. A central topic is the exceptional nature of urban growth in England in the seventeenth and eighteenth centuries, which contrasts sharply with the virtual absence of urban growth in most of continental Europe. This was only possible because of the radical advances in agricultural productivity that was a *sine qua non* for the urban growth that took place. The extent to which London dominated urban

[3] Jevons, *The coal question*, p. 2.

growth in the seventeenth century contrasts vividly with the very different pattern of urban growth in the eighteenth century, reflecting the changing character of the national economy. The far more rapid rise of the English population compared with that on the continent between the mid seventeenth and mid nineteenth centuries was almost exclusively due to the scale of urban growth in England. Linked to the rapid urban growth, there were major changes in occupational structure and in the structure of consumer demand.

Chapter 6 is devoted to the country's population history. For reasons made clear by Malthus in his later writings, in organic economies the demographic characteristics of the country greatly influenced its economic circumstances and prospects. This was especially clear in relation to nuptiality. The conventions governing the timing and extent of marriage in each rising generation in England meant that the level of fertility was sensitive to prevailing economic circumstances, which kept the population a safe distance from the edge of a 'Malthusian' precipice. This in turn implied lower mortality than was common in most organic economies. In a 'low-pressure' system of this type living standards are likely to be higher than in 'high-pressure' systems in which both fertility and mortality are at higher levels. Because of the differing elasticities of demand for primary, secondary, and tertiary products, even modest differences in average incomes can produce significant differences in the structure of aggregate demand that is reflected in a country's occupational structure.

For many decades the release from earlier growth constraints by the increasing use of coal as an energy source was limited by the fact that although coal was widely used to supply heat energy, the sources of mechanical energy were unchanged. An industrial revolution could not be accomplished as long as mechanical energy continued to be provided principally by human and animal muscle. One key sector of the economy, land transport, remained primarily dependent on animal muscle as its energy source until a railway network was constructed in the middle decades of the nineteenth century. Chapter 7 describes the developments in transport taking place from the mid seventeenth century onwards, culminating in the building of the railway system. With the advent of the railway, the steam engine replaced human and animal muscle in powering land transport. More generally, by the mid nineteenth century the steady improvement in the efficiency of the steam engine meant that mechanical energy could be derived from coal as effectively as heat energy. The steam engine became the chief source of mechanical energy for industrial production in general. Once this was the case, the industrial revolution could be regarded as accomplished. Defining the industrial revolution in this way makes it possible also to date its completion, at least approximately.

Chapter 8 reveals the insights into the English economy made possible by the unusual character of the 1831 census, which provides the same level of detail for the smallest unit, the parish or township, as for the county or the country, and distinguishes between types of employment servicing only a local market and those dependent on a wider national or international market. This makes it possible, for example, to demonstrate that by the time of the census proto-industry had virtually disappeared.

Chapters 9 and 10 describe the rapid disappearance during the later nineteenth century of the advantage over continental economies that England had acquired over the three preceding centuries, and suggest the reason for this abrupt change. As long as coal was used only to supply heat energy, most of continental Europe continued to find that wood was cheaper than coal for this purpose, but when the steam engine made it possible to derive mechanical energy from fossil fuel, the situation was transformed. Between the mid nineteenth century and the outbreak of the First World War the growing economic advantage that Britain had enjoyed for two centuries rapidly disappeared. There are also reflections on the nature of the transformation of the economy that took place between the sixteenth and nineteenth centuries, and a brief discussion of the character and scale of change that followed the completion of the industrial revolution. As a coda to the volume as a whole, there is a brief discussion of what might be termed the downside of the industrial revolution, the imminent and growing danger of environmental disaster brought about by the large-scale use of fossil fuels.

The central concept used in providing structure to the description of the interaction between the changes that gave rise to the industrial revolution is the concept of *positive and negative feedback*. In organic economies negative feedback between different factors of production was common. For example, if the population increased it would involve at some point taking into cultivation marginal land, or farming existing land more intensively, or increasing the arable acreage at the expense of pasture, changes which tended to reduce labour productivity, inhibiting further growth and reducing living standards. In early modern England the rising importance of a fossil fuel as an energy source meant that many of the relationships which involved negative feedback in organic economies changed: positive feedback became more common. The growth process tended to foster further advance, whereas in organic economies the reverse was the case. One of the recurrent themes throughout the book is the significance of the replacement of negative feedback by positive feedback patterns in the interaction between different elements of the production system. It was unavoidably necessary to escape from the predominance of negative feedback within the production system if exponential economic growth was to be attained; or, in other words, if an industrial revolution was to take place.

As the subtitle of this volume suggests, it describes change in England and may therefore suggest that the accomplishment of an industrial revolution occurred in England exclusively. Only occasional reference is made to Wales, Ireland, or Scotland. In general, especially in the second half of the period covered, change took place in the British Isles as a whole rather than simply in England but I have focused on England because for some variables, notably but not solely those measuring demographic change, continuous data series are available for England over a longer period than for the other countries in the British Isles.[4] In the interests of simplicity and clarity I have told a story in purely English terms which was increasingly apposite for Britain, and indeed for the whole British Isles, notably from the mid eighteenth century onwards.

[4] It should be noted, incidentally, that in the population data set out in the tables in this volume England does not include Monmouth, even though it was treated as part of England in the early English censuses.

1 Organic economies

Before the industrial revolution all human societies laboured under a common constraint in attempting to increase their ability to produce even the basic necessities of life. Their degree of success in this regard varied enormously. It might seem ridiculous to regard those living in Renaissance Italy as similarly placed to the early tribes of hunter-gatherers. In many contexts such an assertion is indeed ridiculous; but in seeking to put into perspective the radical nature of the change implied by the occurrence of an industrial revolution, it is instructive to explore the sense in which the assertion is justified. All life on earth is dependent on the process of plant photosynthesis, by which a fraction of the energy reaching the surface of the earth from the sun is captured by plants. The energy thus captured creates the base of the pyramid comprising all life forms as, for example, in providing food for herbivores and therefore also indirectly for carnivores. Plant photosynthesis, however, captures only a tiny fraction of the energy contained in incident sunlight. One estimate suggests that 400,000 kilocalories of solar radiation reach each square metre of soil annually, of which 4,000 kilocalories, or 1 per cent of the energy involved, is translated into vegetable matter.[1] Other estimates suggest a lower figure. Pimentel indicates the wide range of efficiency with which different crops capture the energy from sunlight: maize captures 0.5 per cent, wheat only 0.2 per cent.[2] White and Plaskett calculate that the total of solar energy arriving on the surface of the United Kingdom from the sun each year translates into the equivalent of the energy contained in *c*. 26 billion tons of coal, an enormous figure, many times greater than current national energy consumption, implying that a total for England and Wales alone the figure would be perhaps *c*. 16 billion tons.[3] Assuming an average efficiency of energy capture of 0.35 per cent, this suggests

1 Kander *et al.*, *Power to the people*, p. 39.
2 Pimentel, 'Energy flow in the food system', p. 2.
3 White and Plaskett, *Biomass as fuel*, p. 2. Their estimates are made in terms of billions of tons of oil, that I have converted into coal equivalents assuming the quantity of energy in 1 ton of oil as equivalent to that in 1.5 tons of coal.

that the equivalent of the energy in 56 million tons of coal might have been secured from the products of plant photosynthesis in early modern England and Wales.[4]

There are wide bands of uncertainty round any estimates of this kind. It is clear, however, that in reality the energy limit imposed by plant photosynthesis on the English economy was very much lower than any suggested in the last paragraph. Only a part of the land surface of England and Wales consists of farmland or forest. Large tracts are too high, too steep, or too lacking in soil depth to be cultivated or to afford good grazing. Agricultural yields per acre in England in the reign of Elizabeth I were only a fraction of the yields used in making the estimates for crops in the last paragraph, and a substantial fraction of the arable acreage was in fallow each year.

Moreover, there was a wide difference between the energy obtained from food consumption and the energy that this made available to perform work. The plants consumed by people and their draught animals provided the great bulk of the mechanical energy available for production processes, since human and animal muscle provided the energy in question, but a large proportion of the food and fodder consumed served to meet the basic metabolic requirements of the men, women, horses, and oxen concerned. Since only the surplus after meeting these needs was available to perform work, mechanical energy derived from human and animal muscle was only a proportion of the energy represented by the intake of food. For example, at least 1,500 kilocalories are needed each day to keep a man alive even if no work is performed. Therefore, if his daily food intake provides 2,500 kilocalories, only 1,000 kilocalories, or 40 per cent of his total energy consumption, will be available for work. If, on the other hand, his intake is 3,500 kilocalories, this will double the amount of energy he can put to productive purposes since it increases the surplus after meeting basic metabolic needs from 1,000 to 2,000 kilocalories. Both figures are maxima since in the course of an average day much of the energy theoretically available to perform work will be devoted to other activities. Both for men and for draught animals any decline in food intake will have a disproportionate effect in limiting the amount of mechanical work that can be performed. In early modern Europe wind and water power provided only a tiny fraction of the mechanical energy secured from human and animal muscle.[5] In all forms of production,

[4] White and Plaskett also present estimates of the efficiency of energy capture which are higher than those of Pimentel, in the range 0.4 to 1.0 per cent, *ibid.*, p. 2.

[5] For example, in 1820, consolidating information covering eight European countries, Warde found that water and wind provided 1.7 per cent of energy consumption, whereas the combined total for food and fodder, the other two sources of mechanical energy,

whether in agriculture, manufacture, or transport, the ceiling set by the available muscle power severely limited the output that could be attained.

Heat energy came from burning wood; 2 tons of thoroughly dried wood yields roughly the same amount of heat as 1 ton of coal. An acre of woodland has been estimated to have yielded approximately 1 ton of dry wood each year on a sustained yield basis.[6] On this estimate of woodland productivity, therefore, it would be necessary to reserve 2 million acres of land for forest to produce the same quantity of heat energy each year as could be secured from burning 1 million tons of coal. A particular example may serve to illustrate the contrast between the comparative energy poverty of an organic economy and the situation that arose in the wake of the industrial revolution. In early modern England to produce a ton of bar iron using charcoal as the source of the heat energy expended in smelting the ore and in its subsequent processing required the consumption of *c.* 30 tons of dry wood.[7] If woodland had covered 30,000 square miles of the land surface of Britain, therefore, it would have sufficed to produce only about 650,000 tons of bar iron each year. As long as plant photosynthesis was the energy base of all human economies it was clearly physically impossible to construct, for example, large fleets of steel cargo vessels, still less to provide a car for every family.

Plant photosynthesis was at the base of all productive activity in organic economies. What could be undertaken depended on the degree of success that a given community experienced in securing as large a fraction as possible of the energy unlocked by plant growth. The degree of success achieved varied massively between hunter-gatherer tribes and societies with settled agriculture. In relatively advanced organic economies there was sometimes a clear recognition that energy availability set a ceiling to what could be achieved. This was admirably analysed in the writings of the classical economists that are discussed in Chapter 2, but it had been recognised in earlier centuries. The problem was well captured in a picturesque fashion in the writings of Sir Thomas More, when he

was 31.7 per cent of total energy consumption. Heat energy from firewood and coal accounted for the balance, with firewood still the bigger of the two. Since England and Wales was one of the eight countries, the dominance of firewood over coal would be far more pronounced in the other seven at this date. Warde, 'The first industrial revolution', Table 5.1, p. 133.

6 Van der Woude *et al.*, *Urbanization in history*, p. 8. It is suggested that well-managed forests in early modern Europe produced 2 tons of firewood per hectare, or 0.8 tons per acre. This estimate may be slightly pessimistic. I have used a figure of 1 ton per acre in these calculations, but it is simple to establish the implications of making an alternative assumption.

7 Wrigley, *Energy and the English industrial revolution*, p. 16.

reflected on the pressures associated with the expansion of wool production in Tudor times. 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'.[8] If the woollen industry was flourishing and the demand for wool therefore rising, more land would be devoted to sheep pasture, but this must mean less land available to grow corn for human consumption, or less land under forest. Expanding the production of woollen cloth must at some point create difficulties for the supply of food, or of fuel for domestic heating, or for the production of charcoal iron. If the land was the source of virtually all the material products of value to man, expansion in one area of the economy was all too likely to be secured only by shrinkage elsewhere.

The ceiling to energy availability set by plant photosynthesis was intrinsic to the nature of all organic economies, but its existence was of little relevance to the lives of men and women in societies whose ability to gain access to such energy was severely limited by the primitive nature of their technologies. The ceiling set by plant photosynthesis was orders of magnitude greater than the energy to which they had access and was therefore largely irrelevant to their attempts to succeed in raising their 'standard of living'. In contrast, in advanced organic economies a much higher fraction of the energy made available by plant photosynthesis was captured, which brought this ceiling closer and made further advance more difficult. As a background to describing the relatively advanced organic economies of early modern Europe in the centuries that ended with the industrial revolution, it may be helpful briefly to review the two earlier radical transformations of productive capacity that are sometimes mentioned as comparable in importance to the industrial revolution. To do so serves to clarify the nature of the difference between the industrial revolution and the earlier transformations within the setting of an organic economy. The two earlier events in question were the mastery of fire and the neolithic food revolution.

Earlier transformations of energy supply

The mastery of fire

Charles Darwin was very conscious of the significance of the mastery of fire, remarking that, 'This discovery of fire was probably the greatest ever made by man, excepting language'.[9] Before the mastery of fire, the energy

[8] More, *Utopia*, p. 26. [9] Darwin, *The descent of man*, p. 49.