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An Early Energy Crisis and Its Consequences

In the 16th century Britain ran out of wood and resorted to coal. The adoption of the new fuel set in motion a chain of events that culminated some two centuries later in the Industrial Revolution

by John U. Nef

In medieval Europe wood was utilized not only in many types of construction but also in most domestic and industrial heating. Then in Britain in the second half of the 16th century coal came into widespread use as a substitute for wood as fuel. The earliest coal-burning economy the world has known was established first in England and then in Scotland between about 1550 and 1700. This transition from woodcutting to coal mining as the main source of heat was part of an early British economic revolution. The first energy crisis, which has much to do with the crisis we now face, was a crisis of deforestation. The adoption of coal changed the economic history of Britain, then of the rest of Europe and finally of the world. It led to the Industrial Revolution, which got under way in Britain in the last two decades of the 18th century. The substitution of coal for wood between 1550 and 1700 led to new methods of manufacturing, to the expansion of existing industries and to the exploitation of untapped natural resources.

To make these assertions is not to belittle the role of other changes during the Middle Ages and the Renaissance in the coming of our industrialized world. The century before Britain's wood crisis—the 100 years from about 1450 to 1550—was characterized by a new spirit of expansion. Voyages of discovery were launched, carrying explorers to the ends of the earth. The art of printing with movable type spread across Europe, and the production of paper expanded; millions of books were printed and put in circulation. In central Europe, where the major centers of mining and metallurgy were to be found, the output of ores, particularly silver-bearing copper ores, multiplied severalfold. The years between 1494 and 1529 have been described as bringing about a "revolution in the art of war." With the help of the new firearms Spain conquered Mexico and Peru.

These and other innovations increased, directly or indirectly, the need for all existing kinds of energy: the heat provided by wood and the power provided by wind, animals and running water. The need for larger amounts of wood for construction and for heating, particularly for the smelting and refining of ores, called for a substantial increase in the felling of trees.

All Europe felt these pressures, and yet the first large area to experience an acute shortage of wood was Britain. Why did the fuel revolution that led to new uses of heat energy begin in that particular place? Was wood particularly scarce there? It seems to be true that the most populous parts of Scotland (the areas surrounding the Firth of Forth) were barren of trees; a wit from England is said to have observed in the reign of James I that if Judas had repented in the king's native land (Scotland), he would have been hard put to find a tree on which to hang himself! Such an explanation does not fit England. The wood crisis there has to be attributed to the requirements of expanding agriculture, industry and commerce, all stimulated by a growing, shifting population.

It appears that Sweden and the Netherlands were the only other European countries to experience anything comparable to the growth and resettlement of the British population in the period from 1550 to 1700. The population of England and Wales, about three million in the early 1530's, had nearly doubled by the 1690's. The resulting demand for wood for various purposes was further increased by changes in the distribution of the population. In this period the inhabitants of London multiplied at least eightfold, from some 60,000 in 1534 to some 530,000 in 1696.

According to Gregory King's estimate for the latter year, the British capital had by then become the largest city in Europe and perhaps the world. King estimates that England's other "cities and... market towns" had a total population of about 870,000. This means that although only one person in 10 was a "townsman" in the 1530's, one person in four was a townsman in the 1690's. Larger towns meant heavier demands on nearby wood supplies. Moreover, outside the towns there was much migration of the unemployed across the country in search of work. Wherever they found employment, shelter had to be provided, putting still another strain on the forests.

During the reigns of Elizabeth I (1558–1603) and James I (1603–25) this pressure on the supply of trees was reflected in the soaring cost of firewood and lumber for construction. The period from 1550 to 1640 was a time of inflation throughout Europe, but the price of wood in England rose very much faster than that of any other commodity in general use anywhere. Complaints of deforestation came from all parts of the kingdom.

Wherever coal seams outcropped in Europe, coal had been burned in small quantities since the 12th century. (It had been more extensively burned in China earlier than that and also to some degree in Roman Britain.) In Europe during the later Middle Ages peasants had occasionally warmed their homes or stoked their lime kilns and smithies with these "black stones." Why then was coal not widely adopted as a fuel on the Continent and in Britain before the forests were seriously depleted?

In societies earlier than the one that arose in western Europe in medieval times mining was looked on with disfavor. It was often regarded as robbery, even as a kind of rape. Unlike the plow, which made the earth fertile, the pick and shovel removed what seemed to be irreplaceable soil and subsoil.

By the early 16th century a different attitude toward the exploitation of the more valuable underground resources

found expression in two books. In *De re metallica* (1556) Georgius Agricola (1494–1555) ranked the miner's calling higher than "that of the merchant trading for lucre." And in *Pirotechnia* (1540) Vannoccio Biringuccio (1480–1539) advocated an all-out assault on these underground riches. He advised "whoever mines ores... to bore into the center of the mountains... as if by the work of necromancy or giants. They should not only crack the mountains asunder but also turn their very marrow upside down in order that what is inside may be seen and the sweetness of the fruit despoiled as soon as possible."

The new dignity attached to mining was reserved for metallic ores. It did not extend to coal. The medieval craftsmen who needed fuel wanted their work to be beautiful, whether it was for their church or for rich laymen. The unpleasant smoke and fumes of coal therefore limited the market for it. There was little incentive before the mid-16th century to dig deep into the soil in search of this dirty fuel as long as wood was available, and there seemed to be an abundance of that. Biringuccio himself believed the forests of Europe could fill all conceivable future demands for fuel. In *Pirotechnia* he wrote: "Miners are more likely to exhaust the supply of ores than foresters the supply of the wood needed to smelt them. Very great forests are found everywhere, which makes one think that the ages of man would never consume them... especially since Nature, so very liberal, produces new ones every day." Coal is mentioned only once in his long treatise and then just to dismiss it: "Besides trees, black stones, that occur in many places, have the nature of true charcoal, [but] the abundance of trees makes [it] unnecessary... to think of that faraway fuel."

Less than a generation later the English turned to coal under pressure from the high price of wood. By the early 17th century efforts by the government to stop deforestation were felt to be imperative because the shortage of lumber for shipbuilding seemed to threaten Britain's existence. A royal proclamation of 1615 laments the former wealth of "Wood and Timber," the kind of wood that is "not only great and large in height and bulk, but hath also that toughness and heart, as it is not subject to rive or cleave, and thereby of excellent use for shipping, as if God Almightie, which had ordained this Nation to be mighty by Sea and navigation, had in his providence indued the same with the principall materiall conducing thereunto." By the middle of the 17th century coal had proved so useful and was already so widely burned that the British had come to make necessity a virtue. They reconciled themselves to the disappointing failure of their explorers to locate sources of precious metal and of their miners to find much of it in Britain itself. In spite of the smoke and fumes of coal and in spite of a widespread distaste for it, by the time of the civil war in the 1640's Londoners were dependent on the coastwise shipment of coal to keep warm. In 1651 the anonymous author of *News from Newcastle* wrote verses in praise of the new fuel. "England's a perfect World! Has Indies too! / Correct your Maps; New-castle is Peru!... / Let th' naughty Spaniard triumph, 'til 'tis told / Our sooty mineral purifies his gold."

Even earlier, as is made clear by William Harrison's *Description of Britain* (1577) and by a petition London brew-

COAL WAS BRITAIN'S PRINCIPAL FUEL by the end of the 17th century. Coal heavers, such as the ones shown in this print from 1805, handled coal destined for homes and industries across Britain and for many foreign countries as well. In background are coal barges.

ers addressed to Sir Francis Walsingham, Queen Elizabeth's secretary of state (1578), coal was acquiring a new and important place in domestic and industrial heating. The surviving records of customs officials at Newcastle-on-Tyne (and later records of other towns) reveal a continuous and rapid growth in the shipments of coal between 1550 and 1700, first from Newcastle-on-Tyne and then from other ports. These records suggest that the coastwise shipments increased at least twentyfold between 1550 and 1700. Coastwise imports to London grew even faster, probably more than thirtyfold, which is not surprising in view of the multiplication of the city's population in that period. Lord Buckhurst, who became Queen Elizabeth's lord treasurer at the end of the 16th century, required the customs officials during the 1590's to determine the "rate of growth" in coal shipments from Newcastle, thereby introducing a new concept into human affairs. The calculations on which Buckhurst insisted indicated that taxes on coal shipments could be counted on to provide a continually increasing source of revenue, and so taxes on coal shipments were imposed in 1599 and 1600.

The most impressive rises in the growth rate of coal production occurred in the second half of the 16th century and at the beginning of the 17th. In fact, the growth rate in the volume of coal mined between 1556 and 1606 may even exceed the growth rate (computed from less incomplete statistics) in the volume mined during the first part of the 19th century, that is, at the height of Britain's Industrial Revolution. The actual quantities involved in the rapid growth of coal production in the earlier period may seem insignificant today, but it is the viewpoint of the Elizabethans and their immediate successors that needs to be recaptured. To them the expansion in the output of coal must have seemed extraordinarily rapid.

Coal was not only a source of energy but also a spur to technological development. Most products that could be manufactured with open wood fires were damaged by contact with coal fumes. John R. Harris has commented that as a result "coal was hardly ever adopted without significant alteration of industrial processes." Indeed, the technological advances of the Industrial Revolution were largely the culmination of the innovative period associated with the conversion to coal.

New methods of firing had to be developed in which the materials to be heated were protected from direct contact with the burning coals and the gases evolved in their combustion. Otherwise the coal would have had to be reduced to coke and so purged of its noxious properties. After about 1610 glass began to be manufactured with mineral fuel in a variant of the reverberatory furnace, a system that later played an important role in the growth of other major industries. In this type of furnace an arched roof reflects the heat of the burning coal onto the material to be heated, thereby preventing the contamination of the material by substances originating with the fuel. The potash and sand to be melted down to form glass were enclosed in a clay crucible to further protect them from the fumes. Like the reverberatory furnace, the crucible was later employed in many other manufacturing processes.

Over the decades following 1610 new technology brought coal into many kinds of manufacturing. The cementation process for converting wrought iron into steel with coal was introduced between 1612 and 1620. By 1618 a method of baking bricks in coal fires near London was described by the Venetian ambassador in words showing that Italians were no longer disposed to ignore this "faraway fuel" as Biringuccio had recommended. Before the British civil war of the 1640's coke was introduced for the drying of malt in connection with the brewing industry, which had expanded rapidly during most of the 16th century with the spread of hop gardening from the Netherlands.

One of the most important applications of coal following the restoration of the British monarchy in 1660 was in the adaptation of the reverberatory furnace for smelting nonferrous metals. This innovation of the 1680's made it possible to smelt the lead, copper and tin ores of Britain with coal. By the end of the 17th century only the production of pig and bar iron remained dependent on wood. Although the problem was not completely solved until the 1780's, an important step toward its solution was taken in 1709, when coke was introduced by Abraham Darby the elder at his blast furnace in Shropshire. In this kind of furnace the fuel and the ore are in contact. The trouble with Darby's process was that it yielded a kind of pig iron that, unlike the pig iron produced with wood, could not be converted to wrought iron, the form of iron then most in demand. In 1784 Henry Cort invented the puddling process, in which pig iron (even pig iron from a blast furnace) is remelted and manipulated in a

BEFORE THE ADVENT OF COAL wood was the main source of heat energy in Europe. Industrial power was provided by wind, animals and running water. It was often necessary to convert the wood to charcoal by partially burning it in furnaces such as the ones shown here. The wood was piled in stacks, covered with earth and powdered charcoal dust and then burned. The covering kept combustion at a minimum so that the end product was charcoal rather than ashes. For some manufacturing processes charcoal was preferred to wood because it is mostly pure carbon and so yields a greater amount of heat per unit volume of fuel. Illustration is from Diderot's *Encyclopédie, ou Dictionnaire Raisonné des Sciences, des Art et des Métiers.*

grates and brick chimneys manufactured with coal). In spite of its grime and stench coal had brought a new comfort to Britain's damp, chilly climate. Already in 1651 the author of *News from Newcastle* observed that the sacks of coal had heightened the joys of intimacy!

Coal had been so successfully incorporated into the British technology and economy that during the last four decades of the 17th century wood prices stopped rising. Some years ago I ventured a rough estimate of three million tons for Britain's annual coal produc-

THE WOOD CRISIS of the 16th century coincided with the expression of a changed attitude toward mining. Until the Middle Ages mining had been widely considered an affront to nature. In *De re metallica,* published in 1556, however, Georgius Agricola expressed a new respect for mining. This careful account of metallurgy and mining gives a good picture of those industries at about the time when it was first necessary to increase coal production. In this illustration from *De re metallica* a tunnel, *D,* has been cut into a hill and three shafts have been dug from above. Although the mining was facilitated when a shaft connected with the tunnel, not all the shafts were meant to do so. In this case the shaft at *A* will be mined only from the surface; the shaft at *B* connects with the tunnel, and the tunnel will soon connect with the shaft at *C.* Material was hauled vertically out of a shaft with a windlass, which was usually covered with a shed to keep rain out of the shaft. Agricola pointed out that it was desirable to construct a separate building as a dwelling because "sometimes boys and other living things fall into the shafts."

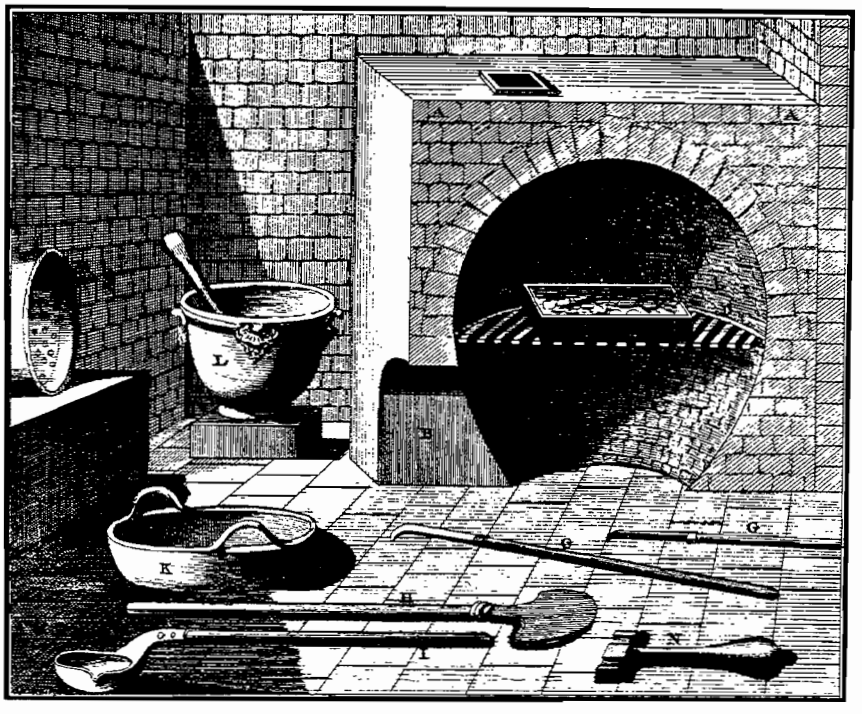
tion in the 1690's. In Harris' opinion that figure "may eventually prove conservative rather than excessive." It appears that at least as much as four times more heating was done at that time with coal than was done with wood. Never before had a major country come to depend on underground resources for the bulk of its fuel.

Although the exploitation of coal had largely solved the fuel shortage before 1700, there was still a wood shortage because other demands for wood had increased. In 1618 a traveler from London described his time as a "rattling, rowling, rumbling age" and remarked that the world runnes on [wood] Wheeles." Great quantities of lumber were required for the construction of the growing number of ships and horse-drawn vehicles needed to transport people and goods across water and land. Moreover, although there was some reforestation during the 17th century, more and more forest was being cleared for farms and pastures. In addition smaller areas were being cleared for the growing metallurgical industries and for the expansion of mining, particularly of coal mining. Britain's forests simply could not keep up with the island's demand for wood.

The British were forced to supplement their domestic supply with imports, mostly from the American colonies and from the Baltic region. (In his *Wealth of Nations,* published in 1776, Adam Smith remarked that in his native Edinburgh "there [was] not perhaps a single stick of Scotch timber.") The imports of wood were paid for in part by the mounting exports of coal and probably in greater part by the mounting exports of textiles manufactured in varying degrees with coal fuel. This foreign trade, and even more the rapidly expanding coastwise trade, had already resulted in the 17th century in the development of a large British merchant marine. New colliers, or coal ships, were designed to carry more coal with a smaller crew, and the coastwise coal trade was considered the chief training ground for seamen, a major factor in Britain's emergence as a sea power.

Yet in some instances coal made Britain less dependent on imported commodities, for example salt. As Robert Multhauf explains in his forthcoming book *Neptune's Gift: A History of Common Salt,* this commodity was an essential one in Europe during the 16th and 17th centuries. In Britain, where food from the sea was coming to occupy a more important place in an increasingly abundant diet, salt was indispensable for preserving fish. In southern and western France salt was obtained by allowing the sun to evaporate seawater in shallow pans, or ponds, but this method was impractical in Britain's climate. In the early 16th century two-thirds of the salt consumed in England had to be imported, mostly from France. Britain's almost total conversion to coal changed the situation. At the end of the 17th century some 300,000 tons, or nearly 10 percent of the coal mined annually in Britain, was burned to evaporate water for the production of salt in England and Scotland. As a result the country had become virtually self-sufficient in terms of salt.

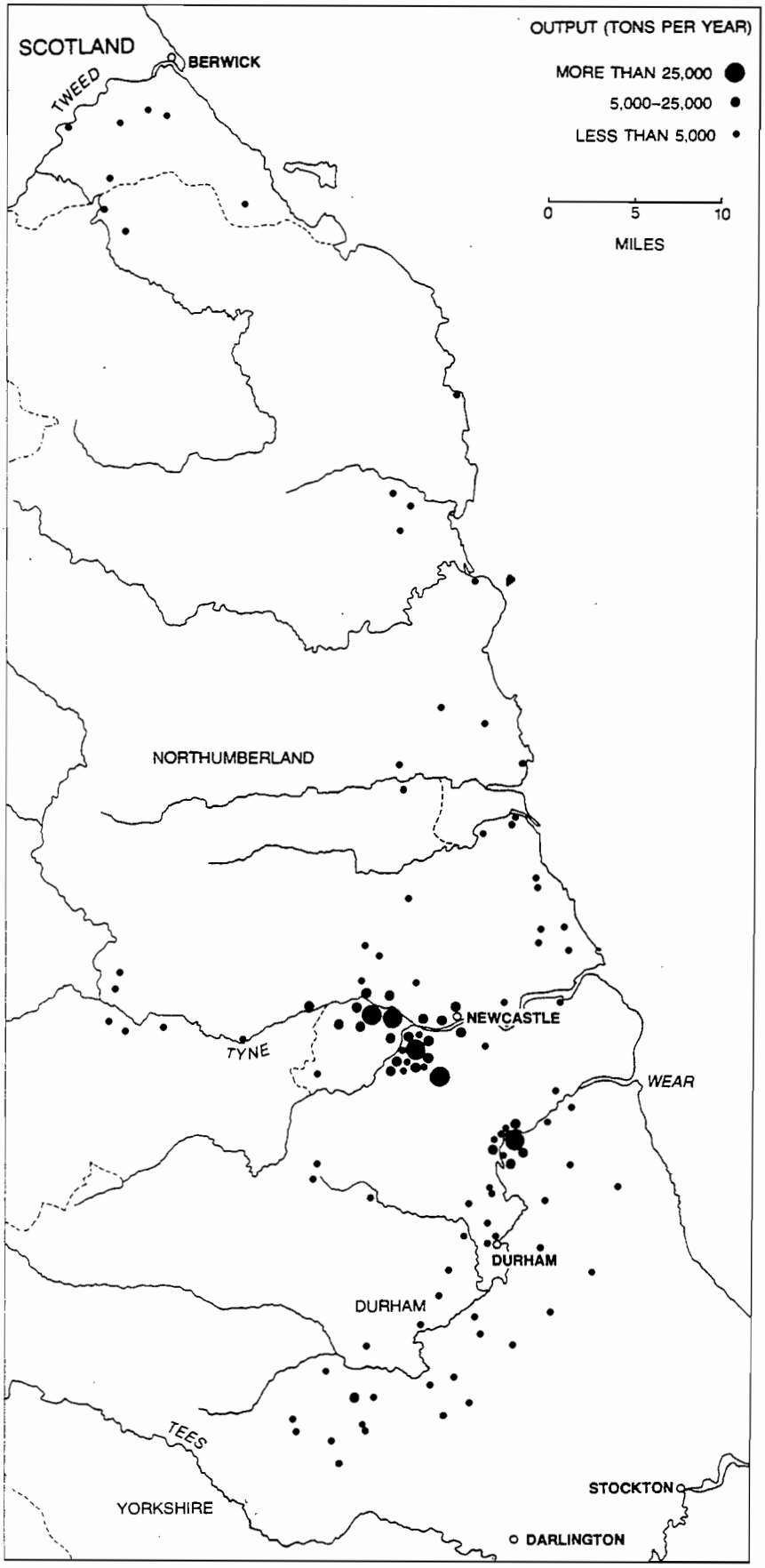
The conversion to a new kind of fuel might have had less effect on the British economy if Britain had been poorly, or even only moderately, endowed with coal. Before the end of the 17th century, however, it had become clear that Britain possessed enormous coal reserves. A piece of coal-inspired technology provided new and reassuring information. The device, called a boring rod, was introduced at the beginning of the 17th century. Early boring-rod surveys were inaccurate, but before the 17th century had ended mining experts were able to determine the thickness and quality of coal seams without sinking shafts. Boring rods had become reliable tools and had revealed a newfound land of plenty under the soil and even under the surrounding seas. Much of the island was seen to be underlain with coal. This trove of energy resources began to exert a pull in the direction of a quantity production that had not been equaled in previous history.



REVERBERATORY FURNACE made possible the utilization of coal in spite of the fuel's reactive smoke and flames. The arched roof of a reverberatory furnace reflects the heat of combustion onto the material to be heated. When the fuel being burned is coal, the arrangement prevents contamination of the product by the substances in the coal fumes. This view of a reverberatory annealing furnace is from the section on coinmaking in Diderot's *Encyclopédie.* Blanks, such as one shown in furnace, had to be annealed before coins could be struck.

It was not until the middle of the 19th century, after an unprecedented acceleration in the rate of growth of production had begun, not until the publication in 1865 of William Stanley Jevons' *The Coal Question,* that some became aware that the coal deposits were exhaustible. By this time resources of petroleum and natural gas were known outside Britain, although neither were much exploited until later in the 19th century. It was not until the 1920's that a few people began to realize the supplies of all fossil fuels had distinct limits.

The shift to fossil fuel in the 17th century led on after 1785 to the aggressive exploitation of the world's vast stores of iron ore. Without the coming of the first coal-burning economy the age of iron and steel might never have developed. The conversion to coal that began in Elizabethan England had further consequences in bringing into being the modern mechanized age. The utilization of steam power and of travel by rail were also vital to the coming of that age. Attempts to build steam engines and to introduce railed ways with horse-drawn wagons in Britain go back at least to the reign of James I, but it was not until 1712 that Thomas Newcomen installed



MAP OF DURHAM AND NORTHUMBERLAND COUNTIES in England shows the approximate locations of collieries in 1635. There were probably more collieries than are shown on the map. Illustration is adapted from map in author's *The Rise of the British Coal Industry*.

at a colliery in Staffordshire a steam engine that actually worked. It was to no small extent the needs of coal mining and coal transport that led to the steam engine and the railroad. Britain's damp climate made the damage of water in the multiplying coal mines a serious problem. Power from horses (which ate costly fodder) and from running water (which required capital for dams and overshot wheels) was diminishing the profits from coal mining throughout the 17th century. The compelling need for more efficient drainage systems in the British coal mines in that early age played an important part in the development of the Newcomen engine. Once these "fire engines" were invented, as John S. Allen and Alan Smith have shown, they spread rapidly across Britain between 1712 and about 1730.

It should be mentioned that coal appears to have been burned for many industrial purposes in China in the Sung era, in the 10th and 11th centuries. The episode was largely forgotten. It clearly did not lead, as it did in Europe much later, to an industrial revolution.

Studies made over the past 50 years, since I published my own two volumes on coal, have shown that the period of Britain's energy crisis—the late 16th and 17th centuries—was also the period of what has come to be called the scientific revolution. The revolution in thinking that brought modern science into being was an even more important factor than coal in the establishment of the mechanized age. By the 1620's and 1630's Europeans were becoming aware of the immense growth in production promised by the development of the new fuel. It was in those two decades that Francis Bacon wrote *The New Atlantis* (1627) and René Descartes his *Discourse on Method* (1637). Bacon's imaginary island over the seas was provided with a great institution of scientific research presiding over human destiny, and he was confident that a new abundance, made possible by the growth of scientific knowledge, would solve intellectual and moral problems as well as economic ones. And Descartes in his *Discourse* was no less confident. Even more specifically than Bacon he foresaw greater output, lighter labor and longer life for human beings everywhere. Even at that time there was talk of airships, submarines, devastating explosives and journeys to the moon. It was the scientific revolution in the late 16th and 17th centuries, together with the economic transformations brought about by the introduction of coal, that gave birth to the industrial world in which we live.

In Britain the period of the onset and resolution of the energy crisis (1550–1700) was characterized by increased returns from labor in all kinds of production. The British statesman and historian Lord Clarendon (1609–1674) was

referring to this prosperity when he wrote that during the period before the 1640's the English "enjoyed... the fullest measure of felicity, that any people in any age for so long time together have been blessed with; to the wonder and envy of all the parts of Christendom." Clarendon did not base his assertion on what would today be considered reliable statistics, and indeed it is not possible to provide such statistics. Yet the new information on English economic growth contained in recent books of Eric Kerridge's and of mine supports Clarendon's statement. Britain, which lagged behind the rest of Europe in many economic areas during the later Middle Ages, was probably ahead of the other European countries in per capita agricultural and industrial output by 1700.

Kerridge has shown that whereas it has been thought that British agriculture was transformed in the 18th and early 19th centuries, the transformation actually took place between the late Middle Ages and the end of the 17th century. In this period, he writes, "the improvement of yields [from farming] must have been enormous. Corn [that is, grain] and grass yields rose about fourfold, and the yields of the fallows [the land not previously tilled] increased out of recognition. All told it is difficult to resist the conclusion that yields rose up to tenfold and fivefold on the average."

In the 1920's and 1930's most students of the coming of industrialism (myself included) accepted the explanations of Karl Marx, Sir William Ashley, Max Weber, Henri Hauser and others. The works of these scholars suggested that the advent of capitalism and of the "capitalist spirit" was the main factor leading to the overwhelming increase in the output of goods and services in the 19th century. I now think that an even more important factor was a growing faith in quantitative progress, in the multiplication of output.

Late in the 16th century a new attention came to be focused on concepts of quantity. The effects of this new concern could be seen in the more exact measurements employed in the developing natural sciences and in the replacement of the Julian calendar by the far more accurate Gregorian calendar. It was also reflected in a series of inventions designed to speed up numerical calculations, one made by Galileo (1564–1642), another made by the Dutch mathematician Simon Stevin (1548–1620) and two more by the Scottish laird John Napier (1550–1617), the originator of logarithms. A sophisticated mathematics—the calculus—was developed first in France after 1620 and more fully later in the 17th century by Newton and Leibniz. The idea of rates of growth introduced during the Elizabethan age brought a fresh precision to economic studies. The new point of view emphasized the probable value of quantitative goals to humanity. The transformation of industrial aims constituted a major advance toward an industrialized world.

In 1697 an Englishman named James Puckle wrote: "Our artisans [are] universally allow'd the best upon Earth for Improvements." This was certainly true in manufacturing that called for efficiency and quantity production. Yet a different evaluation needs to be made of the state of the arts and the luxury crafts in Britain following the conversion to coal. At the juncture of the 17th and 18th centuries Europe was eager to learn more efficient production methods from the British, but the British were equally eager to learn ways of fashioning beautiful products and environments from the Italians, the French and the Dutch. (Nowhere in 17th-century Europe was the quest for beauty and harmony in buildings and furnishings as remarkable as it was in the Netherlands of Rembrandt and Vermeer.) Harris has shown that in the 18th century the British, in spite of their aspirations to high fashion, had great difficulty copying the methods of making high-quality glass that were employed by the French at Saint-Gobain. In Britain the rise of the coal industry had weakened the position of craftsmanship and art as the heart and soul of production.

Moreover, the rise of coal mining had cast a shadow over the laborers connected with coal. Coal miners and coal carriers, stained by the black mineral, were often outcasts. They were seen as black men, and in the 17th century, when real black men were being shipped as slaves from Africa to America, coal laborers were being subjected to a new form of slavery in Scottish collieries and coal-burning salt pans.

As coal spread from Britain to the rest of Europe in the late 18th century and afterward the concern for beauty in manufactures and in the human environment weakened. Throughout history this kind of dedication to beauty has been important in setting reasonable limits to economic growth. The advent of coal seems to have diminished such dedication. The exploitation of the earth's resources has often violated the bounds of good taste. To make the most of these resources calls not only for ingenuity but also for restraint. At present man's dependence on fossil fuels is as problematic as his dependence on wood was some 400 years ago. The best hope for the fruitful exploitation of fuel resources may lie in a renewal and an amplification of the standards of beauty. If humanity is to advance, the making of history must become an art, that is, a search for beauty.