Process Innovation and Changes in Industrial Energy Use

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Summary. American industry in the 19th century switched from wood to coal as its primary energy resource. The history of this switch is reviewed, along with the history of preceding similar trends in Europe and later trends in the switch from coal to oil and gas. Important conceptual advances in the technology of such basic processes as glassmaking, cementmaking, and steelmaking emerged as the switch from wood to coal proceeded in the United States. These advances may have been more important than the relative prices of wood and coal in motivating the conversion of American industry to the use of coal. The historical role of process advances in determining the choice of energy resources suggests that the physics and chemistry of industrial processes may be as important an area of energy research as the various technologies of energy conversion.

As industry developed in the United States through the late 18th and 19th centuries, it initially employed wood and some coal as fuel. Beginning in the mid-1850's, the use of coal as an industrial fuel grew rapidly, and between 1850 and 1870 there was a nearly fivefold increase in the production of bituminous coal. By 1885 coal production surpassed firewood production and continued to grow vigorously, while production of firewood declined, gradually (*1*). By 1930, the production of bituminous coal provided somewhat more than half of the fuel used in the United States, and alone represented twice as much fuel as the total of all fuels consumed in this country during 1900. In about 1920, the production of oil and natural gas, and their use as industrial fuels, began a growth that ultimately exceeded even the previous growth in the use of coal. As coal had replaced wood as the principal industrial fuel, so oil and gas came to replace coal.

Efforts are now being made to predict the possible patterns of industrial energy use in the future. In this context it is of interest to consider the profound changes which have taken place in industrial energy use over the past century. To enter this subject, let us consider the circumstances under which coal largely displaced wood as an industrial fuel.

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Early Use of Coal in the United States

The earliest recorded coal mining in the United States occurred in 1701, near Richmond, Virginia, but commercial mining of coal did not begin in this country until 1745. Coal was discovered in Ohio in 1755, and in 1770 George Washington commented on an Ohio coal mine he had seen. Yet, with concentrated deposits of coal available for exploitation, at presumably very low cost, coal still did not make significant inroads into the market for fuels. In fact, even with American deposits of coal having been identified, most of the coal used in America up until the Revolution was imported from England or Newfoundland. The shortage of coal occasioned by the break with England spurred the growth of American coal mining during the Revolution. Government requisitions of coal in Pennsylvania and Maryland, to support the manufacture of munitions, stimulated the beginning of American coal mining as an industry. Thus, the American coal mining industry began, not as a national response to price, but as the result of a shock—the loss of English coal during the Revolutionary War.

A great discovery of coal was made in 1810 when an unusually violent freshet unearthed a huge coal seam, now believed to have been the Pittsburgh seam, near the town of Barton. Coal from this seam was hauled by wagon as far east as Romney and Winchester. Later it was hauled overland to Westernport, where it was placed on barges and rafts, and shipped to Washington. Yet, even with these early discoveries of coal in rich deposits, where fuel could be picked from the surface of the ground, coal production did not make significant inroads in the market for fuels. It was not until 1850 that coal production reached 10 percent of the fuel provided by firewood. Why was it that it took so long for coal to displace firewood? Why did coal displace firewood?

It has been tempting to dismiss these questions by saying that wood must have become scarce and expensive as newly discovered coal offered a cheaper substitute fuel. Therefore, coal displaced wood. The argument based upon price alone is plausible, but misleading. It neglects other important aspects of the competition between wood and coal, aspects which had a strong influence upon the outcome of that competition and which may well have important implications on the development of future patterns of industrial energy use.

Let us consider the notion that resources of fuel wood were near depletion or were in some sense scarce, as compared with the national demand for fuels during the period 1830 to, say, 1850, when the transition from wood to coal became evident. Between 1850 and 1870 the annual production of fuel wood rose from approximately 2×10^{15} British thermal units to nearly 3×10^{15} Btu (*2*). It then declined again to about 2×10^{15} Btu in 1900.

After 1900 production of fuel wood declined steadily, even during the fuel shortage of the two world wars. However, as this decline in fuel wood production occurred, the total annual volume of wood harvesting rose rapidly. From 1869 to 1923 annual lumber production rose from 12.7×10^9 board feet to 41×10^9 board feet (*2*). These data cannot be translated directly into an equivalent production of fuel wood because they reflect finished lumber taken from the select marketable bole of the tree, rather than the whole of the wood mass (including slash and nonmarketable species, for example) which could be taken for fuel. Nonetheless, the figures do reflect the fact that the wood available, for whatever purpose it might be used, had not been depleted at the time of the interfuel competition of the early 1800's (*3*). To estimate the magnitude that the supply of fuel wood might have attained, one may note that between about 1830 and 1900 approximately 250 million acres of forest land were cleared for farming in the east-

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ern United States (*4*). Most of this clearing occurred after 1850, with the growth of settlements. If one assumes that the cutting of these lands would have yielded ten cords per acre, the total fuel value of firewood which would have been taken as a by-product of clearing would have been approximately 60×10^{15} Btu (*5*). This is somewhat more than twice as much fuel as the entire United States consumed between 1850 and 1900. Indeed, there was no shortage of fuel wood during the competition which was won by coal.

Why, then, was the firewood not used? Why was coal able to capture the industrial fuel market in the face of vast surpluses of firewood? One might suppose that the difficulties of transportation could have made wood a more costly and less attractive industrial fuel. However, difficulties of transportation did not deter those who exploited the forests for logs. They got their merchandise to the very industrial centers in which coal was displacing firewood, so that it could be used for construction. Also, we may note that given large supplies of fuel available at low price, industry might have located so as to exploit it. Few industries moved to the expanding boundaries of the newly cleared farmland.

The price of coal versus the price of fuel wood, as influenced by the costs of gathering and transportation, certainly exerted some influence on the decisions of industry in the period of the interfuel competition. However, the incomplete historical data available to us concerning the price of these two commodities reflect some periods when fuel wood was significantly cheaper than coal.

In 1880 the price of coal, FOB (freight on board) at the mine was $1.25 per ton. It was not until 1899 that this price fell to $0.80, after which year it has risen steadily. Data concerning costs of transportation and distribution of coal in this period are not readily available, nor are data concerning retail prices of coal. However, we may assume that the costs of transporting and distributing fuel wood would not have differed greatly from those of coal, if a wood fuel industry had existed. So, to gain some notion of how the relative price of coal and fuel wood may have influenced the interfuel competition, one might estimate what the value of fuel wood stacked, say, at the roadside might have been, had one been able to sell the heating value of the wood at the same price which was obtained for coal. Taking into account the fact that both the coal and wood must be dried to some extent to yield their maximum heating value, the calculation indicated above will show that fuel wood would have had a value of about $1.20 per cord, stacked at roadside. That is to say that the fuel wood disposed of in clearing farmland would have represented a value of about $12 per acre cleared. Not only was this an extremely high value during the time the clearing took place (1850 to 1900), it even approaches the land prices in the northeastern United States recorded as recently as 15 years ago. One might suppose then, that had there been an industry organized to exploit fuel wood, industry could have sold fuel at a significantly lower price than coal. In fact, one can suppose that *some* fuel wood probably *was* sold at a significantly lower price than coal. Nevertheless, coal prevailed.

How Fuels Are Chosen

Let us return to our original question: Why did coal displace wood as an industrial fuel? There was not an absolute shortage or depletion of fuel wood, which necessitated a switch from wood to coal. Also, price was neither the only nor perhaps even the principal factor in the contest.

Let us reexamine this question. To suppose, as is now fashionable, that industrial fuels will be chosen principally on the basis of price, one must presuppose that the fuels are equivalent in a number of other important respects. For example, one must presuppose that the fuels can be used the same way in the same equipment to carry out the same processes. One must also presuppose that when a transitional competition between two or more fuels arises, such questions as may not be strictly economic in nature (for example, possible modifications of processes) will be addressed with similar energy and intelligence by parties on all sides of the competition. These presumptions are seldom justified.

Consider, for example, the wave of invention which preceded the growth of coal in the United States. Darby, in 1735, invented the first blast furnace in which high-quality iron could be made in large quantity. The basic secret to Darby's furnace was the use of coke produced from coal. Prior to Darby, iron was reduced in furnaces which employed charcoal obtained from wood. But the logistical problems of gathering sufficient charcoal to run such a furnace had always kept the furnaces small (*6*). In the mid-1800's, Bessemer perfected his steelmaking process which further exploited the chemical properties of coal, as well as its heating value. As the technology of coal grew, opportunities to control combustion were developed and exploited. Pulverized coal burners were in use before the turn of the century, affording control of heat release and temperature, which was crucial to development of many industrial processes.

Portland cement, which was invented and patented in 1824 by Aspdin, requires ultimate processing at 1550°C. Coal combustion offered the opportunity to produce Portland cement in large quantity.

The use of coal as a fuel in glassmaking also made possible the execution of controlled processes of mass manufacture, which were not possible in (then) wood-fueled glassmaking (*7*).

Another major aspect of the use of coal as an industrial fuel is that it lends itself to well-controlled gasification. This, in turn, permits even more refined process control than can be attained by way of solid fuel combustion. The importance of the use of gasified coal as an industrial fuel in stimulating the development of new processes may have been immense; in any event, it merits historical study. It is doubtful that the first process for mass manufacture of glass containers, the Owens process, could have been made to work effectively (or at all) had it not been for the use of controlled combustion of gasified coal at one critical stage of the process.

Coal, then, offered not merely the heating value required to run industrial equipment. It offered the opportunity to develop new and more productive processes. This, together with inventive minds which were attracted to examine the possible uses of coal and their implications, had much to do with the growth of coal as an industrial fuel.

This brings one to another aspect of the use of coal. In 1856 Perkins, in England, discovered aniline dyes in coal. This set off not only the chemical industry based on coal products (which soon flowered in Germany) but also created the basis for the growth of the entire field of industrial organic chemistry. The scientific discoveries in organic chemistry attracted talented and motivated people like a magnet (*8*). Although the total fraction of coal production given to chemical products has never been very large, the influence of the chemical industry in attracting human intelligence to the questions of how coal might be used was immense.

So, coal won the contest to replace wood as an industrial fuel because there simply was no contest; the use of coal had on its side the focused intelligence of a large number of the world's most talented scientists, engineers, inventors, and entrepreneurs, all striving to find new and more productive ways to use coal. In addition, the extraction and transportation of coal lent itself to organization as an industry. Fuel wood, on the other hand, was established. It was not organized as an industry, and it attracted no innovative champions to meet the challenge of coal.

That the use of coal attracted talented people does not in itself show that talent was more important than price in determining the outcome of the interfuel competition between coal and wood. One school of thought in economic history holds that it was because of the low price of coal that talent was attracted to its use (*9*). However, this argument is inconsistent with the theory that price is the chief determinant in setting the course of commodity use. If coal had been cheap and if its cheapness had caused its ascendancy over wood fuel, then one would expect that this new cheaper energy source would have been used with profligate inefficiency. But just the opposite was true. The world's genius was focused, in fact, upon finding new, more efficient and more productive means of using coal.

Early Use of Fuel in France and England

England, from the late 16th through the 18th centuries, was beset by deforestation (*10*) and was thus faced with an absolute shortage of domestic fuel wood. The English response to this crisis was to turn to the use of domestic coal. Although coal had been exported from England to the Continent since 1200, it was apparently the shock of the absolute shortage of fuel wood which finally drove the English to exploit their own coal as fuel. There followed a wave of innovation, including the invention of the Darby blast furnace, the construction of inland canals for transport of coal and other goods, the construction of the early steam engine of Newcomen (which was designed to pump water from mines), and other such advances, which collectively gave rise to the British industrial revolution.

During the same time France also experienced difficulties in obtaining sufficient fuel wood. However, these difficulties were associated with practices of wood harvesting and transportation, rather than with absolute deforestation. Although, by the time of Louis XIV, the court believed that a concentrated effort should be made to develop France's coal deposits for fuel, France ultimately did not follow the British example.

French industry, particularly ironmaking and glassmaking, was reorganized to follow retreating forest boundaries (*11*). The forest sites most favorable for such purposes were those near water for power and transportation. These same sites were desired by the navy because they facilitated transportation of the ship timbers which the navy required. Urban growth, much of which followed industry, also drew heavily on these same forest areas for lumber and fuel wood. Thus, although France had abundant forest lands, only limited forest areas were exploited, and three sectors of society, industry, the military, and the citizenry, competed for the wood of these limited areas.

By the early 16th century some French towns had petitioned the king to protect their firewood against the competition of industry. In 1723 Versailles issued an edict which attempted to limit industrial fuel consumption, to protect the (not yet named) consumer. The law provided that no new forge, glass factory, or wood-burning manufacturing plant could be established, nor could an existing one be expanded, near towns or navigable rivers, without a favorable report from the provincial intendant and permission of the court role-general (*12*). Since enforcement of this law was lax, the volume of petitions to the king became immense and, as a result, there developed a complex regulatory system for the allocation of forest resources. At the same time, substantial tracts of forest lands were cleared for farming, near the very towns which had depended on these tracts for fuel wood. There is no evidence that transportation systems to bring fuel wood (or food) from more distant tracts were seriously considered by the government.

Under these conditions the wood supplies diminished, so that by the late 1700's cries of "wood famine" were raised throughout France. Of the three sectors of French society which required wood, the navy was most seriously hurt. The fir species required for mast timbers had been ruined by nearly a century of grazing in the forests; mature oak, required for hulls, had virtually vanished.

The citizenry was the next most severely affected by the dearth of wood. Firewood prices in France climbed 87 percent between 1730 and the eve of the Revolution. Most often the rise in the price of firewood bespoke receding forest boundaries, in the absence of any effective system of transportation, rather than genuine deforestation.

Industry, on the other hand, was little affected by the scarcity of wood. It did not need the high-quality, mature fir and oak, as did the navy. In addition, industry was organized to follow the forest lines, so that costs of transportation, which contributed the greatest component to the price of urban firewood, had less effect on industrial fuel. And, industry used much wood in the form of charcoal, the price of which was determined mainly by costs of processing, rather than by the cost of feedstock.

Finally, insofar as manufacturers' fuel bills were rising somewhat, a number of scientists and entrepreneurs devised improved uses of wood and charcoal in industry; they also enabled industrialists to make use of previously untapped forests. The Marquis de Court found means to raise the yield of iron smelted from rocks by 19 percent, using the same amount of fuel. Buffon devised a forge with natural draft. This eliminated the need for water power to operate bellows, and thus permitted the operation of forges in forest areas far removed from the streams.

In general, the response of French industry to the fuel wood crisis was, in spirit, the same as the approach of "energy conservation" as it is pursued today. This is to eliminate obvious wastes of fuel, to relocate plants, and to apply some innovations to ancillary aspects of industrial processes to improve the use of fuel. But it does not include making major conceptual changes in the processes themselves.

As the French observed the changes occurring in English industry, where coal was introduced to replace wood, they conducted an internal debate on the priorities for the use of fuel. The clergy maintained that the wood required to heat homes should be secured, even if this required denying fuel to industry. Industrialists considered the possibility of switching from fuel wood to coal but concluded that the cost of changing equipment was too high. The French tended toward decision by the (not yet formulated) science of economics. How much this tendency was reponsible for their reluctance to take to great risks reflected by the British action, as opposed to how much this reluctance reflected the absence of an absolute necessity for change, remains an open question (*13*).

The English Experience

It is interesting to examine the history of certain processes through which coal came to be the principal industrial fuel in England in the 19th century. Glassmaking was advanced substantially in France during the last part of the 16th century, and the English and the Dutch both sought French artisans for their glassworks. (Technology transfer it seems, then, as now, is best effected via transfer of persons.) Glassmaking at this time was entirely based on the use of fuel wood. The great glassmaking tradition of England began in 1567, with the construction of two glassworks in Fernfold Wood, Sussex, staffed by imported labor and located so as to exploit the then plentiful fuel wood of the region. Additional glassworks soon were built in other townships in the southeast of England. Each was established to exploit foreign labor and local fuel wood. This pattern of development quickly produced its own problems.

Beginning in Sussex, Surrey, and Kent, where wood for fuel was plentiful, the foreign glassworkers and their descendants migrated from place to place, always driven by the fuel demands of their furnaces. Their progress, and the progress of English deforestation, can be traced by cullet heaps, the ruins of furnaces, and by the distinctive names of foreign artisans recorded in parish registers. The commercial benefits of glassmaking in England, which contributed strongly to the flourishing growth of the British economy under Queen Elizabeth I, soon became an important part of the problem of British deforestation, which the great queen bequeathed to her troubled successors.

British response to this problem was swift. In 1610 a patent had been granted to Sir W. Slingsby for burning coal in glassworks furnaces. In 1615 all patents for glassmaking were revoked, and a new patent was issued for making glass with coal as fuel, in the names of Mansel, Zouch, Thelwall, Kellaway, and Percival (*14*). Simultaneously, the use of wood for melting glass was prohibited. The importation of glass from abroad was also prohibited. In about 1617, Mansel acquired the sole right of making glass in England, and this he retained for more than 30 years.

Ideas Versus Economics as the Force for Change

English decisions were clearly not based on carefully drawn and economically justified plans. The elements in the decision to prohibit the use of wood in glassmaking appear to have been desperation, invention, and arbitrary action, accompanied by a not unpredictable wave of greed (*15*).

The production of glass with coal as fuel was originally a "batch" process, just as was production with wood fuel. The full economic advantages of coal-fired glass production were yet to be developed, and there was still a field of competition between coal and wood as a fuel for glassmaking. The innovations that were to establish the undisputed predominance of coal as the principal source of energy for glassmaking came in the form of broad advances that also affected the use of fuel in other industrial processes. The patents and the royal decree of 1610 compiled the development of a technology for making glass without chemical or mechanical defects by means of coal fuel, and this prepared the way for later and richer innovation.

One major technical innovation in the use of coal was gasification. In the first practical application of gasification, Murdock, between 1792 and 1802, demonstrated the large-scale production of illuminating gas from coal (this art dated back to 1691). In 1799 Lebon obtained a French patent for a process to make illuminating gas from wood; he demonstrated his process in 1802. But wood gas was never to become a major fuel either for illumination or for power.

The first coal gas producers for industrial fuel were built in 1836 in Magdesprung, Germany. These were relatively crude, inexpensive units that produced "low Btu" gas at high temperature and were suitable for use with relatively small furnaces. In 1856, the Siemens company in Germany introduced an improved unit capable of delivering coal gas to several furnaces and suitable for a wide range of industrial uses. In the same year, Perkins in England discovered aniline dye in coal tars, an event that had such an explosive effect on 19th-century science and technology.

The year 1856 marked the emergence of the Siemens brothers as a major source of industrial innovation. From the Siemens company came the regenerative glass-melting tank; this was an adaptation of the Siemens furnace for steelmaking, in which then novel techniques of heat recovery by regeneration permitted, at the same time, (i) maintenance of the high temperatures ($\sim$ 2700°F) required for glass melting, (ii) vastly improved efficiency of fuel use and improved control of quality, and (iii), most important of all, reliable continuous operation. Of all of these advantages, continuous production was the key. By 1952, when Professor F. H. Norton (*16*) published *Elements of Ceramics*, the Siemens' coal gas generators, in combination with Siemens' regenerative furnaces, had become the standard to which all discussions of glass melting referred.

Coal in Iron- and Steelmaking

The first iron foundry in Pittsburgh, established in 1793 by Anshutz, made stove castings. It used local water power and wood fuel. The iron ore it used was transported across the Allegheny Mountains to the site. Although this particular foundry failed within 2 years, by 1840 iron and steel founding had become Pittsburgh's principal industry. However, despite the well-known coal deposits of the region and the existing British technology for using coal-based coke, Pittsburgh iron was smelted primarily from charcoal. It required over 100 years for Pittsburgh to adopt the coal-based technology of ironmaking begun by Darby.

In the mid-19th century two developments in the technology of iron- and steelmaking served to reshape not only the iron and steel industry, but also the market for coal in the United States and abroad. One of these was the invention by K. W. Siemens in England, in 1856, of the regenerative furnace for open-hearth steelmaking and continuous glass melting. Siemens was, according to his biographers, fascinated with Stirling's earlier work on the hot-air engine and, in particular, with the thermal regenerator which Stirling introduced. It was this fascination that stimulated Siemens to apply Stirling's concepts to his own work. The first known application of Siemens' regenerative furnace to glassmaking was in Chances glassworks at Birmingham, in 1861. Because of the combined merits of continuous production, high fuel efficiency, and control of quality, worldwide adoption of the Siemens' glass-melting system came fairly rapidly. With it came a new and unprecedented market for coal.

The application of Siemens' furnace to open-hearth steelmaking came equally rapidly. By 1867 Siemens was successfully producing mild steel in regenerative open-hearth furnaces in his own steel works. Worldwide imitation also followed this success, but not quite at the same rate as in the case of glassmaking. Ironically, the second great technical surge came close on the heels of Siemens' invention and, for a time, eclipsed Siemens' open-hearth process.

The second development, also in 1856, was the Bessemer steelmaking process. It was not until 1865, however, that Bessemer developed his to the point that he could reliably produce specimens of steel and malleable iron. The early response to his process had been cautiously optimistic and encouraging, with due expressions of skepticism by metallurgists. The response to his demonstrations was electric. Andrew Carnegie, upon witnessing Bessemer's demonstration, hurried home to Pittsburgh to announce to his partners, "The day of iron is past! Steel is king" (*17*). Carnegie built a Bessemer plant near Pittsburgh, at Braddock. He and his partners attained phenomenal rates of production with their ever-expanding Bessemer plants, and by 1881 the partnership became incorporated, at a value of $5 million. The Bessemer steelmaking boom, set off by Carnegie, gave tremendous impetus to the coal industry near Pittsburgh (*18*).

The basic concept that made it possible to produce Portland cement continuously was the use of heat recuperation (preheating combustion air, while quenching the "clinker") in a rotary kiln. The additional concept of using pulverized coal as fuel to obtain the localized high-temperature flame required in the final stages of calcining was also important. Both these concepts were embodied in the design of the rotary cement kiln by Hurry and Seamen in about 1895. The rotary, coal-fired kiln revolutionized cementmaking and further increased the demand for coal.

Processes and Fuels

The history of the adoption of coal as the principal industrial fuel shows that the advent of new and more effective processes, which happened to be designed about the use of coal, had at least as much to do with the industrial switch from wood to coal as did the relative prices of these two fuels. The switch in fuels can be said to have been economically motivated, to be sure. However, to the degree that it was, the motivation was based upon holistic considerations, rather than upon the price of the fuel itself. The advantages of being able, for example, to produce glass continuously, in a process fueled by coal, was so important that the price of coal itself was probably of little consequence. It was the widespread adoption of these processes that led to the rapid growth in the use of coal as an industrial fuel after 1850.

The processes that resulted in the adoption of coal as the principal industrial fuel may have had their roots in a period of desperation (the English dearth of fuel) when certain elements of basic science and technology were established. Nevertheless, they appear to have arisen chiefly in a burst of discovery and invention during which the attention of a large number of talented persons was drawn toward coal chemistry and other aspects of the use of coal. The motivation of these persons may, in part, be said to have been economic. The potential, revealed by Perkins' discoveries for the use of coal in applications that had not previously been suspected, certainly must have led many to speculate on the possible economic advances and personal gains to be made. But those who actually developed the new processes seem to have been as strongly influenced by fascination with new ideas as by the possible economic consequences of their work. There is little evidence to suggest that the heroic inventors of 1856 were even aware of the price of coal, much less that they were motivated by price, to direct their thoughts toward the use of that fuel.

There are striking parallels between the later growth of petroleum and the growth of coal. In the same way that the discovery of coal tar dyes by Perkins seems to have galvanized the scientific world and focused the world's talented minds on coal science, the refining of petroleum to provide illuminating oil, light motor fuel, and similar substances seems to have caught the imagination of a later generation of talented persons. The demands for motor fuel, especially from 1915 on, were accompanied by the improvement of refining techniques, the discovery of petrochemicals which had not been suspected to exist, and, in fact, the development of modern day chemical engineering. Coal science could not compete with the attraction of the newly developing fields of discovery offered by petroleum for the talented minds of the world. The full effect of the decline of coal science can be seen, for example, in the history of this field in the United States over the past 30 years. In 1973, one was hard pressed to find academic scientists in this country who were familiar with the properties of coal or the potential for production of synthetic chemicals from coal. Yet, coal is this country's major energy resource.

Edison's invention of electric illumination and the consequent growth of the electric utility industry gave coal a buffer from the effects of its declining attraction for talent. The uses of electricity beyond illumination also attracted great numbers of talented people. But insofar as the use of coal itself in producing electricity was concerned, the chief interests seem to have been combustion and economics. These interests were pursued by those whose basic concern was production of electricity, not coal science. As Sporn (*19*) has pointed out, the cushion which supplying fuel to the growing electric utilities and to the railroads gave to the coal industry was probably detrimental to that industry, and to coal science, in the long run. The latter fell behind as progress toward process innovation based on discoveries related to petroleum science and electricity proceeded rapidly.

The Initiation of Change

It is evident that the changes from one form of energy to another are more often motivated by the overall aspects of a change in process than by the price of energy or other individual economic aspects. Industry changed from the use of wood to coal principally because new and superior processes, which happened to be based on coal, became available. Industrial changes from coal to oil were, most often, similarly motivated. Changes from combustion to the use of electricity in industrial heating (for example, industrial direct heating furnaces or steel preheating by induction) are often motivated by the availability of a superior process, or an entirely new process, rather than by the price of fuel versus that of electricity. In 1927, Trinks (*20*), in his classical work on industrial furnaces, noted that even though electricity is more costly than fuel for heat, "the electric type [of furnace] is preferred because it offers advantages that cannot be measured in terms of fuel cost."

Decisions to change either the form or the mode of industrial energy seem to have a set of common characteristics.

1) The basic motives are usually holistic. To secure the widespread interest required to cause a significant change in the way in which industry uses energy, it is usually not sufficient to offer merely a means of improving the efficiency of energy use. Such means usually entail trade-offs between fuel costs and other costs (capital, labor, administration, for example) of making the improvement. They have, therefore, natural limits; they can be pursued only to the point at which the trade-off "breaks even." However, when a new process emerges to offer the possibility of producing, for example, some substance such as cement, steel, or glass in a radically improved way, the process may be adopted with enthusiasm. Such processes usually entail advances in the efficiency of the use of all factors of production, including

energy. They may also entail changes in the form of energy to be used (for example, electricity versus fuel). The price of energy itself may not be an important consideration in the decision to adopt the new process. Industry is always more attracted by processes of this kind than by opportunities merely to substitute one form of additional expense (capital) for a decrease in another (energy).

2) Those basic process innovations which have led industry to switch from one form of energy to another have been followed by further innovations which increase the efficiency of the process—including the efficiency of energy use—even as the price of the energy used has fallen in response to the broader market created for it by the new process. The efficiency of the use of coal, for example, increased radically after 1856, as coal prices fell. There have been important instances in which process innovation resulted in significant improvements in the efficiency of energy use without affecting in the least the form of energy used. Often these have been motivated by concerns that had little to do with energy directly. One of the most important of these was the relatively recent development by Sir Alaistair Pilkington of the float process for manufacturing flat glass. This process is so much more efficient overall that it has entirely displaced its predecessor, the plate process. The float process saves vast quantities of fuel, labor, capital, material, and all other factors used in the manufacture of flat glass. Its developers were motivated by a desire to do just that. Those who adopted it were motivated by a desire not to become obsolete.

3) One may note that from time to time something happens, be it a crisis, a discovery, a war, or some other compelling event, to draw the attention of numbers of talented and imaginative people to the study of some subject. The subject might be the use of coal, the use of heat, petrochemistry, electricity, glassmaking, or something else. Whatever the subject, it seems that the focused attention of talented and imaginative people can be relied upon to produce innovative advances, advances such as Siemens' regenerative furnace, or Bessemer's convertor, or Daimler's engine, or Darby's blast furnace. These are advances which, because of their overall superiority to previous practices, can secure rapid and widespread adoption. The opportunities embodied in these advances exert a much more powerful influence than do opportunities merely to substitute one thing for another.

Conclusions

There are a number of things about energy research today which one may think represent misplaced emphasis. It seems to be of highly questionable value to attempt to decide which forms of energy to develop from the resources to be available in the future without giving significant attention to the processes for which these forms of energy might be used. One cannot assume that energy will be used in 2010 in the same way it is today. The history of industrial processes seems to show that each one is susceptible to improvement through basic innovation. One may have to wait for a Siemens or a Perkins or a Watt or an Edison to provide the innovation. But, such persons do appear, and, given a reasonable chance, they cause progress, the nature of which is usually unsuspected in advance. The proper field of endeavor in industrial energy conservation would seem to be the physics of processes rather than the use of fuel in existing equipment.

We are about to have to change the basic energy resources on which we operate many of our basic production processes (for example, coal or solar energy will have to be used to replace natural gas and oil in some applications). We will be faced with a wide range of forms in which energy might be brought to a process (for example, coal might be used for direct combustion, or as synthetic gas, or as electricity, or even in some other form). In considering how various new forms of energy might be used to operate a process, especially one that has been conceptually unaltered since, say, 1856, one often finds opportunities to make fundamental conceptual advances. These entail not only possibilities to improve directly the use of energy in the process, but also opportunities to advance overall productivity. The latter category includes opportunities to reduce losses in manufacturing yields, to advance control of quality, and to devise equipment that can operate flexibly according to the demands for production, rather than on essentially a full-time schedule.

It may be useful to give some examples here of apparently promising directions for technical efforts on process improvements.

In metal fabrication it is not uncommon for 50 to 70 percent of the workstock to be cut away as the final part is formed. Alternative techniques, which include electroforming and ionarc spraying, permit one to form metal parts directly to shape. The perfection of technology for fabrication of this type could both save fuel and lead to immense gains in productivity.

In many industries (for example, electronics, stainless steel), high-temperature furnaces that are used only, say, 40 hours per week must remain energized around the clock (this is because of the peculiarities of traditional furnace design). The time is overdue to develop lightweight furnaces with fast response times so that one can shut the unit off when it is not in use. (The furnace must be capable of quickly returning to the desired operating temperature, and there must be suitable control over temperature.) Heating equipment of this sort would be most valuable.

If, in addition to providing fast response time, the high-temperature heating systems suggested above were also to offer advances in the refinement with which one could control temperature, they might lead to substantial gains in munufacturing yields. In certain critical processes, such as production of electronic components, this could be of immense importance. It would provide large indirect savings in fuel (by reducing wastes of material) and, even more important, would provide direct gains in overall productivity.

In specialty steel production, the very reheating furnace that is energized around the clock, to be used only 40 to 80 hours per week, is also the site at which about 4 percent of the entire product of a plant is lost as oxide scale. Techniques of reheating and forming might be developed that would prevent this loss. For example, the stock could be heated and formed under an inert atmosphere or under a vacuum.

High energy lasers can be used for hardening metals. Laser techniques can reproduce the effects of thermochemical hardening (for example, carburizing) and mechanical treatment (for example, shot peening). The laser techniques can be applied virtually instantaneously and they can be applied to highly localized zones on large parts and even to zones of completed structures.

These examples, which offer only an imperfect representation of what may result from a basic reexamination of industrial processes, all entail the application of known effects to already perceived opportunities. What we should expect, on the other hand, is that the problems of energy should motivate the search for opportunities to make conceptual advances in processes. Such advances could range well beyond direct concerns with energy. Thus the emergence of conceptually advanced processes will probably set the future trends in industrial energy use.

References and Notes

1. These data are taken from the *U.S. Statistical Abstracts* (Government Printing Office, Washington, D.C.).
2. Conversion factors are: from British thermal units to joules, 1055; from acres to hectares, 0.4047. One board foot is 1 inch thick and 12 inches square.
3. The peak year for lumber production in the United States was 1901. These high volumes of production were the result of overcutting. Conservation policies instituted under the Roosevelt administration introduced systems of forest management under which lumber production was to be limited to annual growth. During the very period that the interfuel competition between wood and coal was under way, the forests were being exploited at a rate which exceeded their natural capacity to replenish themselves. One might suppose that clever or greedy exploiters of forest lands could have gathered fuel wood (slash, limbs, nonmarketable species, for example) to sell to industry, while taking other more valuable trees for lumber. The marginal cost of gathering otherwise useless wood for fuel, once one had established a basic system for gathering logs of high value, would probably have been rather low; the fuel wood might have been a by-product of the rapidly growing logging industry.
4. B. E. Fernow, *History of Forestry in Europe, the United States and Other Countries* (Univ. of Toronto Press, Toronto, 1913).
5. According to a number of U.S. Department of Agriculture studies [for example, *U.S. Dep. Agri. Bull. 753* (10 March 1919)] a harvest of 10 cords per acre is reasonable, even in the northeastern United States with its short growing season.
6. Approximately 3 acres of trees were required to produce sufficient charcoal to make a ton of iron.
7. The first coal-fueled glass plant in the United States was, in fact, built in Pittsburgh in 1808, by Blakewell. Details of the design of the furnaces and other equipment are not available; it was a batch process plant and the glass produced there was noted for its exceptional quality.
8. The influence of the rapidly developing field of coal chemistry on intellectual life in the second half of the 19th century was far-reaching. This subject is discussed even in the works of radical political writers of the day, including the works of Lenin.
9. According to this school, talent follows money. An alternative view is that money is created by talent.
10. A visit to Nottingham today will illustrate this. The forest that shielded the legendary Robin Hood from his pursuers has been reduced to a few specimen trees.
11. See, for example, D. B. L. Young, "A wood famine? A question of deforestation in the old regime of France," *Forestry* (1976).
12. The notion of the Environmental Impact Statement evidently goes back a way in history. The attempt by the French crown to curtail industrial fuel also might be compared with U.S. Federal Power Commission Order 467 of 1973.
13. Young (*11*), among others, suggests that France's economic and social reorganization to exploit its ready availability of traditional fuels (wood and charcoal) retarded French economic development.
14. J. G. Percival is credited with the introduction of covered crucibles to protect the glass from the products of combustion of the coal.
15. During the English Protectorate patent rights lapsed and certain glass products were once more imported from the continent. In 1663 the Duke of Buckingham obtained a ban on glass imports but he failed to obtain the monopoly over glassmaking which he had sought. Buckingham did operate a glass works which was noted for production of very high quality glass.
16. F. H. Norton, *Elements of Ceramics* (Addison-Wesley, Cambridge, Mass., 1952).
17. S. Lorant, *Pittsburgh—The Story of an American City* (Doubleday, New York, 1964), p. 147.
18. Carnegie was blessed with good luck also. He happened to have available ores that circumvented certain metallurgical problems with Bessemer steel that were not fully understood until the work of Thomas in 1875.
19. P. Sporn, *Technology, Engineering, and Economics* (MIT Press, Cambridge, Mass., 1969).
20. W. Trinks and M. H. Mawhinney, *Industrial Furnaces* (Wiley, New York, 1927), vol. 1.

Industrial Energy in Transition: A Petrochemical Perspective

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Although the growth of the petrochemical industry in the United States is attributable to several factors over the years, one of its basic strengths has always been the abundance of relatively cheap raw materials. Even though the industry has never used more than 8 percent of the petroleum and natural gas consumed in the United States, it produces 80 billion pounds of chemicals annually. Out of this has come a cornucopia of products that has affected our daily living and, indeed, has influenced the form of our civilization. A world without plastics, synthetic rubber, manmade fibers, and pesticides would be a different world from the one we have enjoyed at relatively low cost during the past three decades.

Although the domestic demand for such products continues to grow (6 to 8 percent per year according to recent estimates), the petrochemical industry can no longer look forward to satisfying this growth by relying solely on traditional raw materials that are approaching economic depletion. True, "economic depletion" is a relative term; today, we routinely recover hydrocarbons that were considered "uneconomic" just a few years ago. But the concept of finiteness is now significant in the energy dialogue because the costs of recovering oil and gas have escalated and are approaching, for the first time in history, the costs of utilizing substitutes. The impact of this fact on the petrochemical industry will be sizable, but we in Union Carbide are convinced that both the resourcefulness and the required technology exist to meet this challenge.

Over the years, industry has demonstrated its sensitivity to the dynamics of economics and technology in making decisions about energy. At Union Carbide our own hydrogeneration projects powered some of our earliest operations, and we used coal in some other locations. For many years we found oil and gas attractive as fuels as well as feedstocks, but we have been switching oil- and gas-fired boilers to coal for some time now, in recognition of the scarcity of oil and gas, their increasing price, and their greatly enhanced value as feedstocks.

Boiler conversion alone, however, is not enough. Even if we conserve all the scarce hydrocarbons that we can through conversion, improved efficiencies, and other conservation measures, the economics of feedstocks will continue to signal the need for more radical actions. We see the costs for oil and gas converging with and eventually exceeding the costs for some substitutes by the year 2000. These signals have been clear for years, and we have oriented our research and development to prepare ourselves to make the adjustments. Our goal is to minimize the cost of our feedstocks and thus retain the competitive value of our petrochemical products. We are convinced that we have in hand or under development the technologies necessary to achieve this goal.

To understand the role we see for technological innovation in the petrochemical industry of the future, we must first understand the role of oil and gas in the industry today, the economic and technological forces that will be affecting

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