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Energy Transitions in History: The Shift to Coal

In the Middle Ages, the main energy sources were firewood, charcoal, animals, and human muscle power. By 1860, 93 percent of the energy expended in England and Wales came from coal. The transition was slow and much of it happened before the Industrial Revolution: Coal's share of energy generation in England and Wales rose from 10 percent in 1560 to 35 percent in 1660 and reached 64 percent in 1760, a date that is often taken to be the start of the Industrial Revolution. Why did the transition occur when it did and why was it so slow?

The answers to these questions have four parts. First, the transition required the invention and use of new technology in almost all cases. More rapid technological change sped up the transition. Paradoxically, however, in some instances improvements in traditional technologies extended their useful lives and thus slowed down the transition. Improvements in "old-fashioned" technology were thus one reason why the transition was not faster.

Second, the invention and adoption of new technology were economic decisions that responded to economic incentives, namely prices and wage rates. This is self-evident for adoption, but it was also true of invention. While there are creative aspects to invention, it should not be regarded purely as a result of flashes of genius. In many cases, the ideas behind important inventions were banal. In all cases, time and money were required to convert the idea into an apparatus or a procedure that could work reliably in a commercial setting. Research and development (R&D) was the crux of invention, and it required the allocation of resources to the activity. That was an economic decision that depended on economic incentives. If an inventor imagined that the invention would be worth using, then there was a case for allocating resources to its development; otherwise, there was not. The balance between the potential revenue from the invention and the costs of the R&D determined whether an invention would be made.

Third, between 1500 and 1800, wages and prices in Britain evolved in a unique fashion. Wages rose relative to the price of capital while the cost of energy fell. These changes made it profitable to use new technology that substituted capital and energy for labor. By the eighteenth century, Britain, like the Netherlands, was a high-wage economy. Unskilled workers earned four times the World Bank's subsistence wage of $1.25 per day. In other parts of Europe and in Asia, wages were close to the poverty line. In addition, energy prices on the coal fields in northern and western Britain were the lowest in the world. The relatively low cost of energy used for heating distinguished Britain from the Netherlands.

Fourth, British wages were high and energy costs low because of the country's success in the globalizing economy of early modern Europe. Wages in the Netherlands were also high for the same reason. These countries succeeded in creating large, commercial empires and trading connections that generated high volumes of trade and high demand for the standardized products made in rural and artisan industries. As trade grew, so did the cities. London was the most rapidly expanding city in Europe. Its population rose from roughly 50,000 in 1500 to 200,000 in 1600, to 500,000 in 1700, and to 1,000,000 in 1800. Rapid urban growth led to tight labor markets and higher wages. The growth of rural industries tended to raise wages in the countryside, as did migration to London.

Equally important, the growth of London led to rising demand for fuel in the city center. In the later Middle Ages and into the sixteenth century, the principal sources of thermal energy were charcoal and firewood. As the city grew, prices rose, since the supply region had to be extended to meet the increasing demand, and transport costs for wood fuels were very high. Small quantities of coal had been shipped from Durham and Newcastle to London in the late Middle Ages. Coal sold at about the same price per energy unit as wood through the Middle Ages, but coal use was limited almost exclusively to lime burning and blacksmithing. Its sulfur rendered it undesirable in all other uses or required expensive ways to limit the tendency of coal to pollute. However, as the price of wood rose, wood became a more expensive source of heat than coal. Once the price of energy embodied in charcoal or firewood was twice the price of energy in coal, people tried to substitute coal for wood. This unleashed the process of invention that led to the transition to coal.

We can trace the process of invention in many activities. The focus here is on only one: the use of coal to heat houses. Indeed, this was the most important application, since residential heating and cooking was the single largest use of energy in the eighteenth and nineteenth centuries. The shift to coal in domestic heating occurred in the seventeenth and eighteenth centuries and explains why more than half of England's energy consumption consisted of coal at the beginning of the Industrial Revolution.

As the price of wood in London rose in relation to coal, the incentive to use coal increased. Converting from wood to coal was not, however, simply a question of chucking one fuel rather than the other onto the fire. Switching fuels, in fact, presented complex design problems.

These began with the layout of the house. The typical medieval house had a large hall or room that extended from the ground to the rafters. The fire for heating and cooking was built on a low hearth in the center of the room. Smoke from the fire filled the space above the hearth and exited the dwelling through a hole in the roof. The smoky atmosphere was useful for curing bacon but not entirely salubrious. This design did have two advantages, however. First, the family could gather round the fire, and, second, the fire was away from the flammable walls, making it less likely that the house would burn down. Had one put coal rather than wood on the fire in this house, two things would have happened. First, the sulfurous fumes of the coal smoke would have rendered the structure uninhabitable. Second, and much more likely, the fire would have gone out. For efficient combustion, coal must be confined to a small, enclosed space, unlike the open hearth of the medieval house.

Burning coal, therefore, first required a new style of house. Chimneys were essential, and they were being built in great houses by the thirteenth century. Initially, stone or masonry walls were built in the house, and the open fire was lit against them. A hood above the fire gathered the smoke and led it out through a chimney. Often a small room was built around the fire to husband the warmth. Building chimneys proved expensive and so for centuries they were only in use in the houses of the well-to-do.

The hooded fire was a first step towards coal burning, but it was not sufficient. Fireplaces remained large as long as wood was the main source of fuel. The design was not effective for burning coal, however. An enclosed fireplace or metal chamber was necessary to confine the coal for high-temperature combustion. The coal had to sit on a grate so a draft could pass through. A tall, narrow chimney rather than the wide chimney used with wood fires was needed to induce a draft through the burning coal. This was necessary both to increase the oxygen supply to the fire and to vent the smoke upwards and out of the house, rather than having it blown back into the living quarters. To work well, the chimney had to narrow as it got taller. The termination of this design trajectory was the house designed around a central chimney with back-to-back fireplaces on the ground and first floors. They could burn coal and warm the house without filling it with smoke.

It took a long time and a great deal of experimentation to develop this style of house. Each element had to be perfected. That required trying out many variants to see what worked best. Grates, for instance, could be made from metal or brick. Which was better? How big should the holes be? Such prosaic questions arose with all elements of the heating system. How big should the fireplace be? Should it be made with brick or metal? How could it be designed so that heat projected into the room rather than escaping up the chimney? How tall should the chimney be? How wide? Should there be a taper? How many twists and turns could there be in the flues? How could several fireplaces be connected to a central chimney without smoke passing from one room to the next? And so forth. Not only did the individual elements have to be perfected, but they had to be balanced against each other. Records of some of this work have survived, since in a few cases designs were patented and some people wrote books and pamphlets promoting their work. Much experimentation was surely done without any records being kept. Most of this experimental work was done in London, and the architectural results were destroyed when large parts of the city burnt down in 1666.

The one innovation whose adoption can be roughly dated is the chimney. John Aubrey and William Harrison both remarked on the widespread construction of chimneys in rural areas in the late sixteenth and seventeenth centuries. This is not very precise evidence, but it does indicate that the proliferation of chimneys occurred at the same time that the market for coal took off in southern England.

The coal-burning house presented economic challenges that paralleled the engineering challenges. Had a modern economy faced the challenge of shifting from wood to coal, there would likely have been a large and coordinated research and development program to solve the design problem. Nothing of the sort happened in the sixteenth and seventeenth centuries. Design innovation was left to the decentralized market. Since most of the innovations could not be patented—the taper of a chimney was not a legal novelty, for example—no one could recoup the cost of experiments through patent royalties. As a consequence, experiments were piggy-backed onto commercial building projects. Builders erecting houses could change the design of a chimney to see if it worked better without any great cost or risk. Their motive was to build houses that were more efficient to heat and that would not fill with smoke, since they could sell such a house for more money. If a design innovation proved successful, they or others could extend it and try to make it even better. Copying and elaborating on innovations was how the coal-burning house was developed.

In this model, which I have described as "collective invention," the rate of experimentation depended on the rate of house building, since commercial construction was the activity that financed the experiments.

The economics of collective invention highlights another way in which the growth of London was critical to the shift to coal. The first way, of course, was its contribution to the rising price of wood, which motivated the shift. The second was the building boom, which underpinned collective invention and solved the problems associated with coal-burning. In the sixteenth and seventeenth centuries, London grew rapidly, and a large number of new houses were built in a small area. The high volume of construction provided innumerable opportunities to tack design experiments onto projects that were undertaken for ordinary commercial reasons. The proximity of this building facilitated the sharing of information, allowing builders to extend each other's innovations and perfect the coal-burning house. Furthermore, the need to rebuild so many houses after the 1666 Fire of London created opportunities to quickly shift the facilities for fuel consumption to the burning of coal. Despite cheap coal in the ground, this sort of experimental work would not have taken place in small towns on the coal fields since not enough building was going on there. London's boom created the incentive to shift to coal and subsidized the experiments that were needed to solve the technical problems that arose. The adoption of coal for domestic heating drove investment in production and transportation of coal, lowering its cost even further and driving innovation in many other sectors of the economy toward the use of a different and easily available energy source.

Further Reading

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