

The Invisible Keystone of the Modern World

All animals, including human beings, consume food for energy. Every human acutely recognizes the imperative to eat or perish. This form of energy is not invisible. Similar as we may be to other animals in terms of food, humans uniquely acquired fire, which brought light, warmth, and protection from predators. Of equal importance, fire cooked food, and its advantages separated our evolutionary pathway from that of our other primate cousins.

Wood fires, combined later with beasts of burden and a little water and wind, powered human society for thousands of years. In the 1500s, the enormous energy from coal began to supplant the earlier sources in England. Later, oil, gas, and uranium joined coal as the big-four primary energy sources or fuels. In the late 1800s, a new form of water power, hydroelectricity, joined the big-four fuels, and these five now supply most energy in the world, outside the unique role occupied by food.

Based on these energy sources, people leaped from the agrarian to the modern, industrial world, and the material benefits of the big-four fuels lie beyond dispute and beyond calculation. Despite the keystone centrality of energy to modern human life, most people think little about it. These forms of energy shrink to invisibility, which makes us vulnerable to the problems they pose. Exploring the pathways to fire, food, and subsequently the big four brings the keystone of modern life into focus.

THE FIRST ENERGY TRANSITION: *HOMO EMBRACES FIRE*

Evolutionary processes—long before the appearance of primates—established food as the energy foundation for all animals, but humans are different from other animals in their reliance on cooked food. Although many animals, including nonhuman primates, prefer cooked food to raw, only *Homo* fully mastered the use of fire. Darwin speculated that learning to use fire ranked with language as one of the most important traits determining human evolutionary success. Chimpanzees may be able to understand the behavior of fire and thus avoid wildfires without panic,¹ but they don't regularly make use of it. Only humans fully integrated fire into their normal daily behavior.²

The use of fire for warmth, light, protection, and cooking, however, does not lie far in the antiquity of evolution. In 2012, microscopic remains of plant material, bones, and minerals in a cave in South Africa showed that regular use of fire was occurring in the cave about one million years ago, and the materials were unlikely to have originated in any way other than regular use of fire by *Homo erectus*, a species that appeared between 1.9 and 1.5 million years ago.³ Other firm evidence for fire dates to about 780,000 years ago at Gesher Benot Ya'aqov in Israel, before the evolution of *Homo sapiens*.⁴

Archaeological evidence of fire is persuasive that early hominins used it regularly, but anthropological findings suggest that hominins began to use fire about the time that *Homo habilis* disappeared and *Homo erectus* appeared. Significant reductions in the size of teeth and the volume of the gut suggested *habilis* maybe and *erectus* for sure relied on cooked food. It is easier to digest, and organisms extract more energy from it than they do from raw food. In addition, reliance on cooked food requires considerably smaller amounts of time devoted to eating and chewing.⁵

Homo erectus possessed distinct traits consistent with survival by the use of fire in addition to its smaller gut and teeth. This hominin had lost the ability to move about on all four limbs and to climb trees adroitly. It slept on the ground, and to avoid predators it may have used fire for protection as well as warmth and light. The finding of regular use of fire by *Homo erectus* in South Africa one million years ago supports these inferences.

If *Homo erectus*, an evolutionary predecessor of *Homo sapiens*, had mastered fire, then in all likelihood use of fire was an integral part of human life from before the time that modern humans evolved. Now

only *Homo sapiens* regularly and mandatorily uses fire, and no people live without it. If this reasoning is correct, then mastery of fire became “natural,” and traits supporting the mastery of fire lie in the human genome. Only *Homo*, the primate genus that completely embraced fire, colonized the entire globe in ever increasing numbers. Embrace of fire was evolutionarily very successful, and, as some have quipped, perhaps *Homo sapiens* should be named *Homo incendius*.⁶

THE SECOND ENERGY TRANSITION: *HOMO SAPIENS* LEARNS TO FARM

Until about 10,000 years ago, *Homo erectus* and then *Homo sapiens* survived and expanded to all continents except Antarctica. Populations grew slowly and, based on changing climates, sometimes contracted. Human life relied on a foundation of food to run bodies and fire to heat, light, cook, and protect against predators. Survival of the species required no further advance in the mastery of energy, but a few scattered settlements built a new energy economy by domesticating plants and animals for agriculture, a change that vastly increased the availability of food and thus energy supplies.⁷ Farming and animal husbandry may have originated with improvement of climate after the last ice age, and it enabled settled living as opposed to nomadism, hunting, and gathering.⁸ Settled living in turn enabled the rise of cities, written languages, social divisions, and vastly faster development of new or more refined materials like ceramics, metal tools, and jewelry.

Anthropologists named this change the Neolithic Transition, but this book uses the term *Second Energy Transition*. No comparable name demarcates hominins before and after fire, but here it's called the First Energy Transition. Embrace of fire and agriculture underlay a lifestyle that persisted in nearly all human cultures from about 10,000 years ago to 1600. By that time, some hunting-gathering cultures survived using only gathered food and fire, but most people derived most of their food energy from domesticated plants and animals and “extra” energy from wood fires. Some people supplemented food and fire with windmills and waterwheels to harvest small amounts of energy from wind and falling water.

This was the agrarian economy in which most people tilled the soil and a much smaller proportion served as merchants, artisans, scholars, priests, soldiers, government servants, and rulers. Civilizations rose and fell in Asia, Europe, Africa, and the Americas, and these various cultures

steadily increased both technical prowess and academic learning. A hallmark of all agrarian economies, however, was that they drew energy supplies solely from the yearly input of solar energy. Photosynthesis made “biomass,” which provided food, feed for animals, fiber for clothing, and woody materials for fire, tools, and shelter. Wind and falling water came indirectly from the heat of the sun.

The historian Alfred Crosby named *Homo sapiens* “children of the sun.”⁹ They were much more energy-rich than they had been as hunters and gatherers, but their material wealth was constrained by the annual input of solar energy harvested by plants, windmills, and waterwheels. Greater amounts of stable food energy fueled population growth that could not have occurred based on the food supplies available from hunting and gathering.

In the minds of classical economists like Adam Smith, David Ricardo, and Thomas Malthus, the creation of wealth depended on three elements: labor, capital, and land. Land, however, really represented energy, because photosynthesis for food, feed, and fiber depended on the amount of land controlled.¹⁰

Classical economists, especially Malthus, were highly pessimistic about the improvement of material living conditions above subsistence levels. For Malthus, a small minority, through provident behavior, might aspire to a more comfortable material standard of living, but the vast majority of humanity must live with much less. As Malthus famously said, the geometric potential for population to increase would always in the end outpace the ability of land to provide more food and other goods. If population levels dropped, then the bulk of humanity might temporarily have a richer life, but the proclivity to reproduce would in the end bring population levels back up to the maximum that land could support. At that point, mortality would balance fertility, and inevitably, Malthus argued, most people would lead an impoverished life of bare subsistence.

THE THIRD ENERGY TRANSITION: *HOMO SAPIENS* CREATES THE MODERN WORLD

People living in “developed” countries think of themselves as “modern,” based on democracy, nation-states, individualism, economic systems to organize capital investments for growth, science, industry built with new technology, and the idea of progress. Sometimes modernity distinguishes itself from predecessors with negatives: not feudal, not an

absolute monarchy, not agrarian, not rural, and not superstitious. In a modern society, most people live in cities and do not farm, the biggest contrast with agrarian societies.

A modern person's material life has far more "stuff" and "conveniences" than even royalty and the wealthiest premodern societies commanded. What medieval monarch in Europe, for example, could enjoy a hot shower with clean water by turning a valve, a ride to another continent in a comfortable jet, painless surgery to heal an injured joint, and instantaneous communication with his far-flung armies?

Material abundance characterized the "modern world" as much as did the standard components: nation-states, democracy, large business organizations, and scientific enlightenment. A philosopher living in Britain, France, or the United States in 1800 could point to great changes in politics, new scientific knowledge, and new ways of organizing economic activity, all in a nation-state that transcended individual leaders and governments.

Yet the vast majority of people in these three countries remained mostly rural and lived very much like their ancestors of 1,000 or even 6,000 years earlier. They farmed with human and livestock muscle power. If they traveled at all, it was on foot, horseback, or wind-driven ship. Their housing and water supply had changed but little. At night, the world darkened except for the feeble light of candles. They had a few more iron, bronze, or brass tools and ornaments. Maybe their clothes included textiles woven in the newly mechanized mills of Lancashire, but probably they wore homemade clothes. A person from 2000 suddenly launched backward to 1800 would be hard pressed to feel that he or she was still in the modern world, even if democracy, freedom from royal tyranny, and scientific knowledge animated public conversations.

The transition from premodern to modern life, in short, rested heavily on material shifts in living circumstances. Without the huge shifts in material life, most of which occurred after 1800, life in the 2000s would have continued to look amazingly like that of over 200 years ago, which in turn looked not all that different from 8,000 years ago. Mastery of energy sources and technology created the Third Energy Transition with major consequences, but all too often the centrality of energy remains underappreciated and ignored.

The economic historian E.A. Wrigley, in his studies of the English industrial revolution, rectified the oversights about energy. He had a vastly richer set of concepts from the physical and biological sciences on which to draw compared to Smith, Ricardo, and Malthus. After the

mid-1800s, the physical concept of energy, defined as the ability to do work, became a fundamental part of science, and scientists could measure it quite precisely in units like joules, kilowatt-hours, and calories.

Wrigley drew from biology and ecology to embrace the concept of ecosystems with energy flows and material cycling. British ecologists in the 1920s and 1930s had borrowed from economic thinking to integrate ideas of producers, consumers, ecosystems, efficiency, and energy flow into biology.¹¹ Wrigley returned the favor by bringing the refined concepts of ecologists back into economics.

He noted that agrarian civilization rested on “organic energy” supplied entirely by the annual flux of solar energy into the biosphere.¹² People harvested this energy directly as food and feed produced by photosynthesis and indirectly from livestock that fed on plants. Firewood plus other plant and animal products supplied fire for light and heat, which had many uses. People also harvested smaller amounts from wind and water power, both driven by solar energy.

Increasing use of coal in place of firewood started in England in the 1500s and ultimately underwrote a new energy economy and vastly expanded the industrial revolution. These events moved first and fastest in England and were virtually complete by 1850.¹³ Wrigley named the new regime the “mineral energy economy,” which eclipsed the older agrarian “organic energy economy.”¹⁴ Agriculture and animal husbandry didn’t cease, of course; they remained the primary source of food and feed for almost all of an increasingly large human population. Firewood remained important in economies not yet industrialized.

Wrigley reconceptualized the industrial revolution, which for him rested on the immense supplies of energy that coal provided compared to that supplied by the organic energy economy. It’s not that other factors and changes weren’t also important as causes or consequences of the Industrial Revolution. To ignore the liberation of human life from the constraint of the annual flux of solar energy, however, was to miss the main point.

Wrigley was one of a long string of historians who attempted to make sense of the industrial revolution, which was so easily visible after 1850. For example, Arnold Toynbee, in his 1884 essay, *The Industrial Revolution*, generally received the most credit for the term, and he celebrated the increased abilities to make things for an easier life. But he lamented the unevenness with which the benefits were shared among different classes of people. Political reform, argued Toynbee, must spread the benefits more evenly.¹⁵

Karl Marx also postulated that human beings had reached a new stage of development in which dearth of material goods should no longer plague human life. Like Toynbee, Marx argued for more equal sharing, but he argued that this would require a revolution driven by the working class to sweep away the capitalist class.¹⁶ William Stanley Jevons took quite a different tack from Toynbee and Marx: he worried about the future supplies of coal and the possibilities for continued expansion of the British economy. For Jevons, the issue was how to keep the good times rolling in the face of projected future rises in coal prices.¹⁷

Economists and historians focused on the multiple dimensions of the industrial revolution.¹⁸ How did labor and capital form in factories? How did growth of national and per capita income cause or change in the industrial revolution? When and why did labor move out of agriculture into cities and factory work? What inventions of new machines drove the productivity of labor upward? What role did coal play? Why and when did the changes in England spread to other regions and countries? What consequences followed?

All of these perspectives are valuable, but they reflect the invisibility of energy that characterized the 1900s. Yes, energy involved ideas, costs, politics, social impacts, and technology, but in the 1900s scholarship too often took energy for granted. Wrigley, in contrast, focused on energy as a *sine qua non* in the modern world. In the 2000s, climate change, health effects, geopolitical tensions, and the difficulties of procuring fossil fuels demand a focus on the pivotal role played by energy.

The Third Energy Transition developed between about 1600 and the 1950s. It began with the sustained increase in the use of coal in England at the start of the 1500s. Increasing use of coal continued in the 1700s through 1900s, supplemented with petroleum, natural gas, and hydro-power. The last fuel of the Third Energy Transition came in the 1940s and 1950s when three countries started to use the heat of uranium fission, first for explosives and then to make electricity. Controlled fission made uranium, plutonium, and thorium into actual or potential fuels to produce heat.

Like the fossil fuels (coal, petroleum, gas), uranium is a mineral fuel, mined from the earth. Heat from all four of these mineral fuels frees humanity from the constraint of annual fluxes of solar energy to the earth. Each of the four fuels is also “energy dense”; that is, each can provide high amounts of heat per kilogram of mass compared to, for example, firewood, solar, and wind energy (for more details, see appendix 2). In addition, like the other fuels, uranium creates benefits as well

as problems (chapter 7). It thus shares many important characteristics with coal, petroleum, and gas, which makes it fit easily into an assessment of the Third Energy Transition.

Compared to the unknown but considerably longer time it took to make the Second Energy Transition (the Neolithic development of agriculture), the Third was amazingly fast. Wrigley puts its beginnings in 1600. Its reality didn't become clear until the mid-1800s in England, a period of about 250 years, or about ten generations. After the mid- to late 1800s, numerous philosophers tried to assess the big change—where it came from, how it progressed in England and many other countries, and whether its benefits could be transferred.

The Third Energy Transition includes the industrial revolution but moves considerably beyond it. Energy industries developed new fuels, vastly expanded the rate of energy production, spread globally (although not evenly), and found a bewildering array of applications not imaginable in 1600 or even in 1800. In the half century since the 1950s, no new “mineral fuels,” as Wrigley calls them, have joined the fossil and nuclear fuels, although work continues on the hope of adding nuclear fusion. But development of new energy services shows no abatement.

If only benefits—and no problems—flowed from the Third Energy Transition, then the rest of the story might consist only of triumphs. For better or worse, however, that's not how things worked out. The radical transformation of human society by the Third Energy Transition has not yet ended, but its side effects now threaten to overwhelm the benefits (see chapters 6 and 7). Quite possibly the problems will even destroy the civilization built on the Second and Third Energy Transitions.

If citizens, consumers, and leaders were fully informed about the roles of energy, then the downsides of “mineral energy” might not constitute such a serious problem. Unfortunately, low energy literacy dominates social and political conversations, and some either fail to see or simply deny any serious problems. Others acknowledge the problems, but solutions commensurate with the magnitudes of the threats continue to elude nations around the world.

We'll delve into the downsides and solutions later (chapters 5–11), but first I want to explore the Third Energy Transition in more detail. How and when did it occur? What actually changed? What effects followed? Questions like these illuminate energy's role as a keystone of modern life, the modern state, and modern science.

Various steps defined the Third Energy Transition. Step 1 was the embrace of coal as a replacement for firewood. This step enabled the

first escape from the constraints of the organic energy economy. Steps 2 and 3 each started with new inventions and their spread. Step 2 used heat to produce motion with the “atmospheric engine” of Thomas Newcomen and, later, the “steam engine” of James Watt. Step 3 changed motion to mobility by adapting steam engines to power ships and locomotives. Steps 1 through 3 alone profoundly altered Britain between about 1600 and 1830, and the technologies on which they depended began spreading around the world, a process still not complete.

STEP 1—FROM WOOD TO COAL FOR HEAT

At one level, coal replacing wood involved no significant change, because the use of coal for heat already had a long history by the 1500s. People in Roman Britain made systematic use of coal for heating and forging iron, and trade routes took it to areas like the Fens on the southeastern coast in exchange for grain and pottery. Earlier uses of coal dated to the Bronze Age, about four thousand years ago. When the Romans left Britain, however, coal use declined.¹⁹

After 1500, firewood became quite scarce in some areas of England, which led people in those areas increasingly to turn to coal for heat.²⁰ Access to firewood and coal depended on transport costs; coastal routes, rivers, and eventually canals made coal cheaper than firewood if the latter had to be hauled overland.²¹ In England, shortage of firewood developed earlier than in continental Europe, because the long, fast-flowing rivers of the continent allowed reliance on firewood imported from distant mountainous areas. England, in contrast, did not have large areas of mountainous woodlands, but its rivers and coastline easily supported long-distance hauling of coal.²²

The switch from firewood to coal reflected changes in Britain’s environment, especially changes driven by human population size. At the Norman Conquest in 1066, Britain’s population was probably about one million.²³ By 1300, it increased as much as threefold, leading to increased clearing of land for agriculture. Woodlands covered 15 percent of Britain at the time of the conquest but only 10 percent by the mid-1300s.²⁴ About one-third of England’s people died in the plague years beginning in 1349, which diminished pressure on woodlands and generally led to better living conditions for those who survived.²⁵ The population recovered to over 4 million by 1600 and over 5 million by 1700. Increased clearing of woodland for agriculture and increased use of firewood again shrank Britain’s supply of wood fuel.²⁶

London became a big user of coal by the early 1300s, because heavy clearing removed woodlands ever farther from the city and coal was easily imported from the north of England via coastal shipping routes. Coal use steadily increased again after 1560 and by 1700 comprised 50 percent of the total energy consumption in England and Wales.²⁷ By 1700, woodlands had again shrunk, to less than 10 percent of Britain's area and could not match the heat produced by the over 2 million tons of coal then produced. The switch to coal was not entirely popular, and critics bemoaned the way coal smoke fouled the air.²⁸ Nevertheless, its heat proved so valuable that people tolerated the nuisance.

So long as coal was simply burned for heat, the embrace of coal looked very much like the long-standing use of firewood. By the early 1600s, coal had replaced firewood and charcoal as a source of heat in brewing and distilling; making bricks, tiles, glass, pottery, nails, cutlery, and hardware; producing salt, sugar, and soap; and smelting and casting brass. In many cases, coal mining formed part of the operations of making a commercial product, especially salt in Scotland, bricks in Lancashire, and copper smelting in Wales.²⁹

Inventions, however, opened the door for coal to take on even more new tasks previously not possible. Undoubtedly one of the most important inventions came from Abraham Darby's use of coal to make coke for smelting iron for casting, probably in 1708–9. Prior to Darby's work, iron smelting required charcoal from wood. Either coal or wood could heat iron for forging, but the chemical processes involved in smelting iron worked better with charcoal. Darby's success probably stemmed from the properties of the coal he used, and he continued to have problems with some batches of iron made from coke.³⁰

Energy in England and Wales changed drastically between 1560 and 1850. Draft animals and firewood figured prominently and coal very little early in the period. By later in the period, draft animals were somewhat more important, firewood essentially disappeared, and coal took first place as a source of heat. The total energy available expanded more than twenty-eight times in the period 1560–1850, and the amount of energy available per person expanded by more than five times.³¹ In sharp contrast, the energy use per person in Italy in the period 1861–70 matched that of England in 1561–70. In other words, Italy lagged behind England in changing its energy use by at least three hundred years (figure 1.1)

As markets for coal expanded after the mid-1500s, landowners sought to join or increase the production of coal. Colliers dug mines

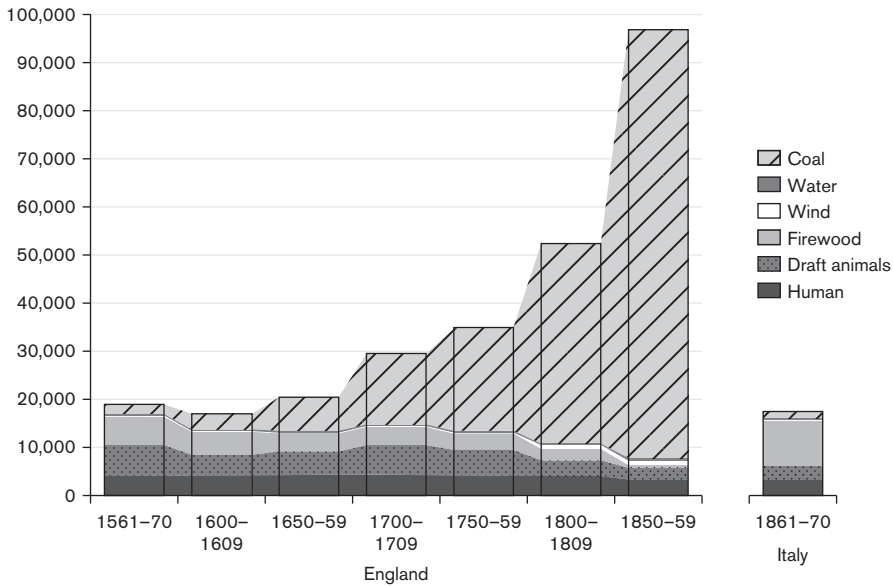


FIGURE 1.1. Annual energy consumption per head (megajoules) in England and Wales 1561-70 to 1850-59 and in Italy 1861-70.

SOURCE: E. A. Wrigley, *Energy and the English Industrial Revolution* (Cambridge: Cambridge University Press, 2010), figure 4.1, p. 95, used by permission of the author.

increasingly deeper into the ground in search of the fuel. Digging deeper unfortunately uncovered more than coal, because water flooded the mines, and mining therefore entailed getting the water out. Pumps run by men, draft animals, and water power at first sufficed to clear the water, but these methods were expensive and had limits.³² Thus miners and engineers began to search for an alternative way to remove the water from mines. This search led directly to Step 2, the ability to use coal to pump water.

STEP 2—FROM HEAT TO MOTION

The first invention addressed a long-standing need: to move things without using the muscle power of people or other animals. Wind and water power had successfully satisfied this need in limited circumstances long before coal became an important fuel in Britain. Water power drove the hammers of fulling mills for making wool textiles and of forging shops that turned pig iron into wrought iron. Wind drove sailing

vessels and windmills for pumping water. Both water power and wind, however, were in limited supply, not always available when needed, and geographically constrained.

Breakthroughs in moving things came first with water. This was no coincidence, because water is heavy as well as vital. Hauling it vertically or horizontally demands considerable energy or work. From time immemorial, people have had to secure reliable access to good water, and they have always sought to minimize the work needed.

During the 1500s and 1600s, various inventors in Europe sought ways to use steam to move water. They combined the use of expanding steam to move a piston in a cylinder with the use of steam on condensation in a cylinder to create a partial vacuum.³³ Although most devices did not work very well, Thomas Savery (ca. 1650–1715), from Devon in England received a patent for his machine.

Savery's machine condensed steam to make a vacuum and suck water into a container, thus putting air pressure to useful work. It then drove water out of the container by using steam pressure. This was the first practical pump run by atmospheric and steam pressure, but atmospheric pressure could not raise water more than about 20 feet, and steam pressure to empty the container lifted not much more than that. His patent, "Raising water by the impellent force of fire," ran from 1698 to 1733 and significantly affected the device invented by Thomas Newcomen.³⁴

Newcomen (ca. 1663–1729), also from Devon, became an ironmonger in Dartmouth in about 1685. Ironmongers engaged in retail sales of iron goods, manufacturing of iron tools and devices, and regional trade in these goods. Newcomen probably had blacksmithing skills, and his partner, John Calley, had experience working with iron, brass, copper, tin, and lead. In addition, Newcomen had talents in design and engineering, and Calley was a plumber and glazier. Regional trade routes took Newcomen to Cornwall and Devon on business trips, so he had firsthand familiarity with the problem of water in mines.

Historical archives are too spotty to document when Newcomen first conceived his engine or the details of the arrangements he made with Savery to protect his engine under Savery's patent. Nevertheless, Newcomen's engine successfully pumped water from mines using the heat of burning coal. Miners widely adopted it during the 1700s, and some of his engines continued working well into the 1800s. Fire under a boiler made steam, the steam was injected into a cylinder with a piston that rose due to the downward pull of a counterweight and steam pressure, cold water condensed the steam and created a vacuum, and atmospheric

pressure pushed the piston down, which in turn pulled a beam down and actuated a pump to bring water out of the mine (figure 1.2). The first engines were probably placed in use around 1710, but the engine built at Dudley Castle in 1712 worked very well and established the reputations of Newcomen and Calley.³⁵

It is unlikely that Newcomen himself thought he was launching a “Third Energy Transition.” Instead, it’s more reasonable to think that he saw a problem—water that had to be removed to work the mine—and figured out a way to solve it. Many of the mines produced coal, so fuel supplies were readily available and cheap. Scarcity of firewood may or may not have affected Newcomen’s thinking. Nevertheless, Newcomen’s device, a new energy service, launched a deluge of inventions and innovations over the next two and a half centuries, all of which depended on the ability to make heat move things.

In 1733, Newcomen’s engine lost the protection of Savery’s patent, which opened the door for many more people to further improve the design.³⁶ In 1759, Watt, a Scottish instrument maker and surveyor, thought about the potential for steam to create movement and propel a vehicle. Watt also experimented with a device, the digester, or what would now be called a pressure cooker. Again he was seeking insights into making steam produce motion.³⁷

The real breakthroughs began in 1763, when Watt tinkered with a model Newcomen engine at the University of Glasgow. He was perplexed at the large amount of steam required and the difficulty of making the model work for any significant time. Watt found that most of the steam in the Newcomen engine served only to reheat the cylinder after it had been cooled to condense the steam and make a vacuum. Watt’s experiments also showed that steam itself possessed a great deal of heat, and Watt saw steam as the product of a chemical reaction between heat and water,³⁸ a view no longer held. In 1765, Watt realized that condensing the steam in a separate container, not the cylinder with the piston, would enable the cylinder to stay hot and thus require less steam and less fuel.³⁹

Watt moved the condensation of steam to make a vacuum from the cylinder to a separate condensing vessel. Watt also separated the cylinder and piston from the atmosphere and relied on the expansive force of steam alone to push the piston once a vacuum had been formed on the other side of the piston. His first patent in 1769 makes clear that the claim to novelty stemmed from the economy of fuel use.⁴⁰

Watt’s changes also made the engine a “steam engine,” one that worked by the expansive force of steam, not an “atmospheric engine”

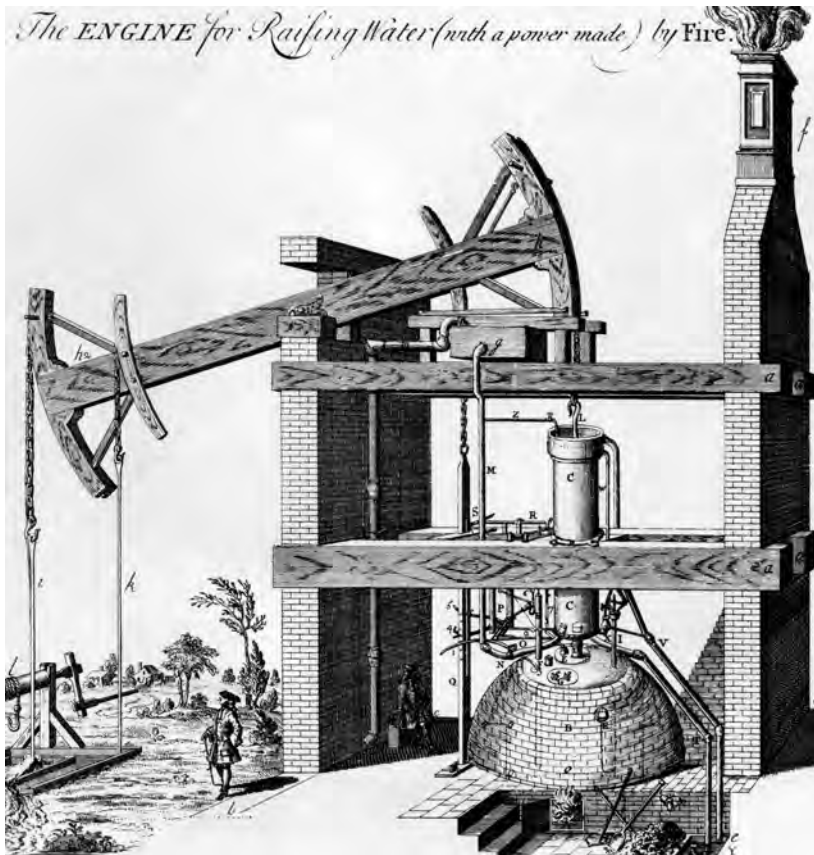


FIGURE 1.2. Newcomen engine used to pump water out of coal mines in England. The Newcomen atmospheric engine was the first to have a “walking beam” pivoted arm (left to upper center) to transfer power between the piston (at right end of arm) and the pump rod (at left end of arm). The boiler (bottom right) released steam into the cylinder containing the piston, forcing the piston up and the rod down. As the valve between the boiler and piston cylinder closed another opened that sprayed a small quantity of cold water (from the tank labeled g). This caused the steam in the cylinder to condense, creating a partial vacuum. The weight of the atmosphere forced the piston down and the rod up. Opening of the valve between the boiler and cylinder restarted the process. Walls of the building housing the engine not shown.

SOURCE: Science Photo Library Ltd., London. Used by permission.

like Newcomen's. Both, however, turned heat into motion by making steam, replacing air with steam in a cylinder, and then rapidly condensing steam to make a vacuum and thus making a piston move.

The fame and fortune that came to Watt for his inventions was more than sufficient to earn him a place in the pantheon of inventors, but the first markets for the new engines remained exactly the same as those for the Newcomen engine: mines flooded with water. Had the use of steam engines gone no further than pumping water out of mines, the scope of the Third Energy Transition would have remained modest at best. Watt himself and many subsequent inventors, however, went far beyond the vexing problems of miners.

Watt's contributions after 1769 lay in three major arenas, and collectively these developments set the stage for the vast array of changes of the Third Energy Transition. First, he continued improving his steam engine in ways that made it even more efficient in terms of fuel use and eminently more suitable for applications beyond pumping water from mines. His subsequent patents involved the capacity for rotary motion in addition to up-and-down motion of a mine pump, more even delivery of power through the piston's cycle of motion, and better control of the magnitude of an engine's power (figure 1.3).⁴¹

Second, Watt and his manufacturing partner, Matthew Boulton (1728–1809), developed an industrial complex in Birmingham, England, that efficiently made and installed engines in many locations, earned money, and used public policy to serve the proprietors' interests.⁴² Starting in 1776, Boulton and Watt successfully sold and installed steam engines. Most of their first customers were metal mines in Cornwall, where coal was expensive. Their business model rested on fuel economy: they took royalties amounting to one-third the value of the coal saved compared to that consumed by a Newcomen engine. Later sales came from all over Britain and abroad. Of equal importance, Boulton and Watt successfully obtained an extension of the 1769 patent to 1800. The original patent would have expired in 1783, and the two partners knew that it was not worth the capital investment needed in Birmingham without patent protection.⁴³

The patents of the 1780s drove their business success. Almost 2,200 steam engines were operating in Britain during the 1700s. Of this total, over 1,400 (about 64 percent) began operation between 1780 and 1800.. Watt-type engines (manufactured by Boulton and Watt) comprised 478 of the total (22 percent). An additional 63 Watt-type engines made in violation of the patent brought the total to 541 (25 percent). Many of

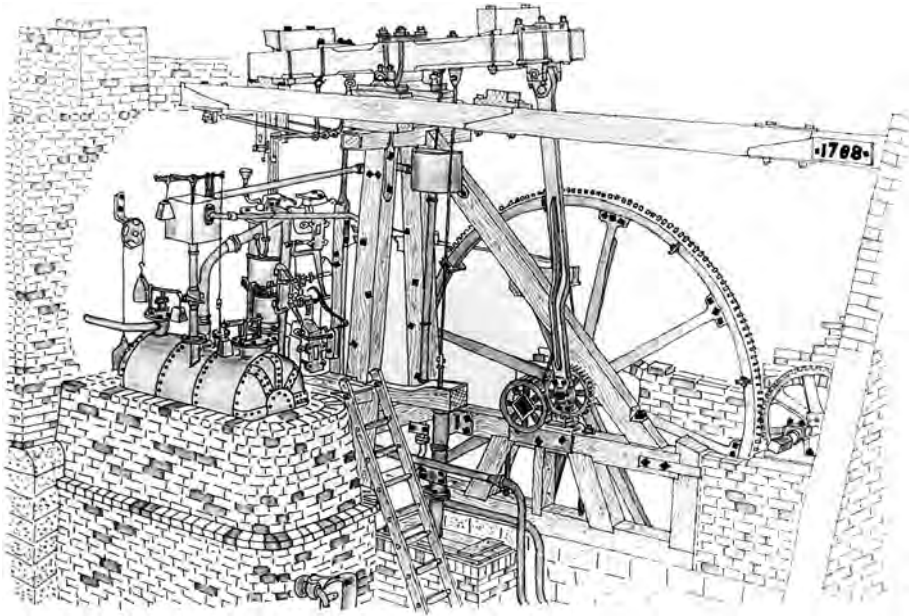


FIGURE 1.3. Watt steam engine. In 1788 James Watt designed and built a beam engine the sole purpose of which was to provide the rotary drive for the lapping and polishing machines at Matthew Boulton's Soho Manufactory at Handsworth in Birmingham. This engine is possibly the most famous rotary beam steam engine in the world, and it is now preserved in the Science Museum, South Kensington, London. The Lap Engine is one of the first engines in the world to have its power output rated in horsepower. The drawing shows how the engine would have appeared in 1788 when it was first assembled at the Soho Manufactory. The flywheel is 16 feet in diameter. This type of engine was used to drive machinery that had previously been driven by horses; customers asked James Watt, "How many horses will one of your engines replace?" A simple calculation established that the engine would do the work of ten horses and became Boulton and Watt's standard 10-horsepower engine; in 1788 this engine cost £800.

SOURCE: Drawing and text by David K Hulse (www.davidhulse.co.uk), used by permission.

the new installations produced rotary motion rather than the up-and-down motion of a water pump and thus rivaled water power for the first time. Rotary engines came into use in manufacturing, such as in textile plants. Boulton and Watt didn't have a monopoly on the market, but they were the biggest company, and no rivals came close to their sales.⁴⁴

Watt's engine, along with Newcomen's, founded a new economy based on mineral fuels. Newcomen atmospheric engines, in fact, totaled 1,022 (47 percent) of the total installed engines in the 1700s, despite the vast increase in the more efficient and more versatile Watt-type engines in the last part of the period.⁴⁵ Firewood, water power, draft animals,

and human muscle power all continued as important sources of energy into the 1800s, but the steady growth of skills in using coal and steam surpassed other sources for moving things.⁴⁶

The steam engine launched a powerful positive feedback loop, first in England, where water pumps at mines made coal cheaper and more plentiful, which made it easier and cheaper to make iron, which made it cheaper to make steam engines, and thus begin the loop again. This positive feedback loop catapulted Britain to freedom from the constraints of the organic energy economy. The wealth of England, based on coal, iron, and steam engines, powered military and political power across the globe, a new global economy, and the growth of the British Empire, which far surpassed all previous imperial ambitions. To be sure, many other factors contributed to the changes England underwent, but without the ability to turn heat into motion, it is unlikely that a small island could have achieved such political and economic power.

England's triumph of being the first to turn heat into motion was not, however, a secret that could be kept. As soon as it became clear that turning heat into motion was possible, clever engineers in Europe, the United States, Japan, and elsewhere began to imitate the British. Exporting the devices helped transfer the skills needed to build and run heat engines. No country that embraced the energy cornucopia of mineral energy has ever turned its back on it. Material wealth, money, and power captivated societies, and a steady stream of new applications of heat-into-motion begun in the 1800s and has not abated.

Retrospectively, it's possible now to see that Step 2 stimulated the development of the science of heat in the 1800s. Heat could produce motion, and motion could produce heat. In the process, energy was neither created nor destroyed; it just changed form. As simple as this concept seems now, such was certainly not the case in 1700. Chapter 2 delves into these developments.

STEP 3—FROM MOTION TO MOBILITY

Easy mobility permeates every nook and cranny of modern life: commerce, urban design, the food system, education, health care, entertainment, recreation, and more. Lack of mobility separated premodern from modern lifestyles. The first efforts to achieve mobility from coal's heat predate Newcomen's engine, but success came over a century later.⁴⁷

For millennia, people had moved themselves and their goods over land and water with muscles as well as wind. Travel overland was