Energy for
the 21st Century

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COAL

Coal suffers from an incredibly bad image. It has few advocates other than the hundreds of thousands whose livelihoods depend on mining and burning coal by the trainload for generating electricity. No one strikes it rich in coal; that metaphor is reserved for oil. For some, coal brings back an image of coal miners who go in hock to buy a set of tools when they are young and quit decades later with black lung, still in hock to the company store. That might be one of the better images. Another would be the mangled bodies of miners caught in mine mishaps or those trapped by cave-ins awaiting their fate in pitch blackness. Still another would be youngsters harnessed to sleds dragging coal up narrow underground passageways on their hands and knees like pack animals or straddling precariously above fast-moving conveyor belts of coal, picking out the rocks. For still others the image of coal is as a pollutant of the first order that has to be eliminated under any or all circumstances. Nothing short of unconditional surrender can appease these environmental militants.

Yet, at the same time, this biomass fuel from ages past is irreplaceable and absolutely essential to ensure that the lights go on when we flick the switch. World coal consumption, essentially stagnant during the 1990s, surged by 47 percent between 2000 and 2008. Not only is the world consuming more coal, but its share of the energy pie increased from 23.4 percent in 2000 to 29.2 percent in 2008. Coal is becoming more important as a primary source of energy, not less as many people desire. Wishful thinking will not make coal go away, but there are ways to alleviate the worst of its adverse environmental consequences. This chapter reviews the history of coal, its importance in today's economy, and what is being done to overcome its principal drawbacks.

THE FIRST ENERGY CRISIS

The first energy crisis was associated with living biomass (wood). It was an on-and-off-again crisis that extended over centuries. One of several reasons why the natural growth of forests could not keep up with the axe was glassmaking. Glassmaking has a long history, going back to about 3000–3500 BCE, as a glaze on ceramic objects and nontransparent glass beads. The first true glass vases were made about 1500 BCE in Egypt and Mesopotamia, where the art flourished and spread along the eastern Mediterranean. Glassmaking was a slow, costly process and glass objects were considered as valuable as jewels; Manhattan Island was purchased from the Indians for $24 worth of glass beads, and Cortez was able to exchange glass trinkets for gold!

The blowpipe was invented in Syria around 30 BCE. Using a long thin metal tube to blow hollow glass shapes within a mold greatly increased the variety of glass items and considerably lowered their cost. This technique, still in practice today, spread throughout the Roman Empire and made glass available to the common people. Transparent glass was first made around 100 CE in Alexandria, which became a center of glassmaking expertise, along with the German Rhineland city of Köln (Cologne). During the first golden age of glass, glassmaking became quite sophisticated. For example, glassmakers learned to layer transparent glass of different colors and then cut designs in high relief. All these achievements in glassmaking were lost in the 400s with the fall of the Western Roman Empire.

The so-called Dark Ages take on new meaning with the disappearance of glassmaking, but vestiges of glassmaking remained in Germany, where craftsmen invented the technique for making glass panes around 1000 CE. These were pieced together and joined by lead strips to create transparent or stained glass windows for palaces and churches. The second golden age of glass started in the 1200s when the Crusaders reimported glassmaking technology from the eastern Mediterranean. Centered in the Venetian island of Murano, glassblowers created Cristallo glass, which was nearly colorless, transparent, and blown to extreme thinness in nearly any shape. In the 1400s and 1500s, glassmaking spread to Germany and Bohemia (Czech Republic) and then to England, with each country producing variations in type and design of glass objects. The ubiquitous glass mirror was invented comparatively late, in 1688 in France.[1]

Glass is made from melting a mixture of mostly sand (silicon dioxide) plus limestone (calcium carbonate) and soda ash (sodium carbonate) in a furnace, along with glass waste, at a temperature of around 2,600–2,900°F. Considering what has to be heated to such high temperatures, clearly glassmaking was an energy-intensive process that consumed a lot of wood. As forests were cleared, glassmaking furnaces were moved to keep close to the source of energy rather than moving the source of energy to the furnaces. The first energy crisis began when English manors for the rich and famous were built with wide expanses of glass panes that opened up their interiors to sunlight. Not only did this put a strain on wood resources for making the glass, but also on heating since interior heat passes more easily through a glass pane than a stone wall covered by a heavy wool tapestry.

The growing popularity of glass was not the only villain responsible for deforestation. Part of the blame lies with the increased demand for charcoal used in smelting iron, lead, tin, and copper. Consumption of these metals increased from a growing population, greater economic activity, and an improving standard of living as humanity emerged from the deep sleep of the Dark Ages. Deforestation started around London in 1200 and spread throughout the kingdom. By the 1500s metal ores had to be shipped to Ireland, Scotland, and Wales for smelting, deforesting these regions in turn. One of the economic drivers for the founding of the Jamestown colony in Virginia in 1607 was to take advantage of the New World's ready supply of trees to make glass for export to England. The rapidly escalating price of firewood, the economic consequence of deforestation, provided the necessary incentive to search for an alternative source of energy. The final answer to the energy crisis was not deforesting the living biomass of the New World, but burning the long-dead biomass of the Old World.

THE ORIGIN AND HISTORY OF COAL

Switching from wood to coal had an environmental consequence. Living plants absorb carbon dioxide from the air, which is released when they decay. For sustainable biomass energy, carbon dioxide is simply recycled between living and dead plant matter and its content in the atmosphere remains unchanged. One way to decrease the amount of carbon dioxide in the atmosphere is to increase the biomass, such as planting trees on treeless land (afforestation), but this is neutralized when living and dead plant matter are once again in balance. The other way is to interrupt the decay process. And this is what happened eons ago when huge quantities of dead plants were quickly submerged in oxygen-starved waters. This delayed onslaught of decay interrupted the natural carbon dioxide cycle.

The partially decayed plants submerged in swamps first became peat. Peat has a high moisture content that is squeezed out if buried by silt of sand, clay, and other minerals from flowing water. Continued burying, either by the land submerging or the ocean rising, added sufficient weight to transform the original deposits of sand and clay to sedimentary rocks and peat to coal. Three to seven feet of compacted plant matter is required to form one foot of coal. Some coal veins are 100 feet thick, which gives one pause to consider how much plant life is incorporated in coal. Most coal was formed 300–400 million years ago during the Devonian and Carboniferous geologic epochs when swamps covered much of the earth and plant life thrived in a higher atmospheric concentration of carbon dioxide. The interruption of plant decay by the formation of massive peat bogs removed huge amounts of carbon dioxide from the atmosphere, clearing the way for a more hospitable environment for animal life. However, some coal is of more recent vintage, laid down 15–100 million years ago, and the newest coal has an estimated age of only 1 million years. When coal is burned we are completing a recycling process interrupted eons ago, or much more recently for those who believe that coal stems from Noah's Flood.

Peat bogs are found in Ireland, England, the Netherlands, Germany, Sweden, Finland, Poland, Russia, Indonesia, and in the United States (the Great Dismal Swamp in North Carolina and Virginia, the Okefenokee Swamp in Georgia, and the Florida Everglades). The high water content has to be removed before peat can be burned as a biomass fuel whose heat content is much lower than coal. Peat is burned in Ireland for heating homes and in Finland for heating homes and generating electricity as a substitute, along with wood waste, for imported fossil fuels. Peat is also mixed with soil to improve its water-holding properties and is a filter material for sewage plants. Once removed, fish can be raised in the resulting pond or, if the peat bog is drained, agricultural crops can be grown, or the peat bog can simply remain fallow. There is always the possibility that these peat bogs may one day become coal beds if buried by hundreds of feet of silt and water.

As in many other areas, the Chinese beat out the Europeans in burning coal. Coal from the Fu-shun mine in northeastern China was consumed for smelting copper and casting coins around 1000 BCE. In 300 BCE the Greek philosopher Theophrastus described how blacksmiths burned a black substance that was quite different from charcoal. From evidence in the form of coal cinders found in archaeological excavations, it is known that Roman forces in England burned coal as a fuel before 400 CE. Although the Romans did not record burning coal, they did record a "pitch-black mineral" that could be carved into trinkets for adorning the human body. That pitch-black mineral was an especially dense type of coal. Like glassmaking, burning coal for heat and blacksmithing and offerings to the gods, plus carving into trinkets for the fashionable of Rome, disappeared along with the Roman Empire. We presume that ever-expanding human knowledge being passed on to following generations has always been ongoing, is ongoing, and will always be ongoing. This, as history clearly shows, is an unwarranted presumption.

The English rediscovered coal in the 1200s during an early episode of deforestation around London, about the same time that the Hopi and Pueblo Indians began burning coal to glaze their ceramic ware in what is now the U.S. Southwest. After the coal gatherers picked up the coal lying on the ground on the banks of the River Tyne near Newcastle, they began chipping away at the exposed seams of coal in the nearby hillsides. Coal mining started when holes became tunnels that bored deep into the thick underground seams of coal. A new profession and a new class of people emerged, ostracized by the rest of society by their origin (displaced peasants) and the widely perceived degrading nature of their work. Coal miners as individuals were at the mercy of the mine owners until they learned to band together for their mutual benefit and protection, giving birth to the modern labor movement.

And there was plenty of incentive for miners to band together as the coal miners bored deeper into the earth. Mining is a very dangerous occupation. Cave-ins can trap the miners. If not immediately snuffed out by the falling rock, they remain trapped, awaiting rescue or dying from asphyxiation or starvation. To combat the peril of cave-ins, miners bonded with huge rats that lived in coal mines by sharing their meals with them. Miners remained alert to the comings and goings of the rats on the theory that rats could sense a cave-in before it occurred, not unlike rats deserting a sinking ship. Perhaps miners' casualty lists best document the perspicacity of rats to sense impending disaster.

In addition to cave-ins, coal miners had to contend with poisonous gases. Mining could release pockets of carbon dioxide or carbon monoxide, odorless and colorless gases of plant decay trapped within the coal seam that quickly killed their victims by asphyxiation. Canaries were the best defense since their chirping meant that they were alive. When they stopped chirping, they were already dead, a dubious warning system at best. A third colorless and odorless gas was methane, also released by mining operations when they exposed pockets of natural gas embedded in the coal seam. Unlike carbon dioxide and monoxide, methane is lighter than air and combustible. As methane accumulates along the ceiling of a mine, it eventually comes in contact with a lighted candle where it either burns or sets off a horrific explosion, depending on its concentration. A new professional, called, euphemistically, a fireman, would wrap his wretched body with wet rags and crawl along the bottom of the mine holding up a stick with a candle at the end, hoping he would discover methane before it was sufficiently concentrated to set off an explosion. Now all he had to do was hug the mine floor while the methane blazed above him.

Coal found in the hills around the River Tyne was moved down to the river and loaded on vessels for shipment to other parts of coastline England, notably London. Access to water provided cheap transportation on ships whereas the overland movement of coal on packhorses was prohibitively expensive. Roads hardly existed and, where they did, deep ruts made them impassable for heavily laden horse-drawn wagons. By 1325, coal became the first internationally traded energy commodity when exported from Newcastle to France and then elsewhere in northern Europe. Thus, coal saved not only the English but also the European forests from devastation. The saying "carrying coals *to* Newcastle" originally referred to something only a simpleton would do since Newcastle was the world's first and largest and most famous coal-exporting port. Six and a half centuries later, coal was carried to Newcastle when Britain began importing coal.

Burning coal made an immediate impression on the people. In 1306, the nobles of England left their country estates to travel to London to serve in Parliament, as was their custom. This time there was something new in the air besides the stench of animal dung, raw sewage, and rotting garbage. The nobles did not like the new pungent aroma spiced with brimstone (sulfur) and succeeded in inducing King Edward I to issue a ban on burning coal. It is one thing for a king to issue a ban, and quite another to enforce it, the classic limit of power faced by parents of teenagers. Regardless of the king's edict, the merchant class of newly emerging metallurgical enterprises had to burn coal because wood was not available in sufficient quantities around London, and what was available was too expensive. Simple economics overruled the king's ban. The fouling of the air of London and other English cities remained for centuries to come. It is hard to imagine that the charming English countryside we know, speckled with quaint towns, cottages, and farms was once, like the eastern United States, nearly one continuous forest.

From the beginning, coal was a matter of dispute between the church, which happened to own the land where the coal was found, the crown, which coveted this natural resource, and the merchant class that transformed coal into a considerable amount of personal wealth. As church, crown, and capital struggled over who would reap the financial benefits, merchant vessels were built to ship coal on the high seas. This, in turn, necessitated building naval vessels to protect the merchant fleet from marauders and pirates. The English also imposed a tax on non-English vessels carrying coal exports, which greatly favored the building and manning of English ships. In this way, coal contributed to making England a sea power and is, therefore, partly responsible for the emergence of England as the world's greatest colonial power. Growth of sea power put more pressure on forests for lumber to build ships and, in particular, trees fit for masts, which eventually would be harvested in English colonies in the New World.

The Black Death did not enhance coal's reputation as its victims turned black while smelling brimstone in the air from burning coal, widely interpreted as to where they might be heading. The Black Death wiped out about one-third of Europeans. The depopulation of London meant less coal had to be burned, improving the quality of its air, and forests regained a toehold in the countryside. The reign of Elizabeth I was marked by increases in population and economic recovery after the Black Death, spurring demand for firewood. She greatly expanded the English Navy to defend the kingdom against the Spanish Armada, increasing the demand for lumber and masts to build warships and charcoal for smelting iron for ship armament. This again put pressure on the kingdom's forests, resulting in widespread deforestation throughout England and another steep rise in the price of firewood.

The adoption of the chimney in London homes in the 1500s allowed for the conversion from wood to coal for heating in the early 1600s, a conversion already completed by industry. While the ability of chimneys to keep the heat inside and channel smoke outside was an advantage for those who dwelt inside, the same could not be said for those who ventured outside. Appalling amounts of acrid smoke eroded and blackened stone in statues and buildings, stunted plant life, affected the health of the population, and made black and dark brown the colors of choice for furnishings and fashion.

London was not the only city that suffered from severe air pollution. During the rapid advance of the Industrial Revolution in the nineteenth century, Manchester became the center of British textile manufacturing and Pittsburgh the center of American steelmaking. The former suffered mightily from coal burned in steam engines to run the textile machines and the latter from coal consumed in making steel. Not all cities suffered equally. Philadelphia and New York were spared at first because of rich anthracite coalfields in eastern Pennsylvania. Anthracite, a hard coal of nearly pure carbon, burns with little smoke. Unfortunately, anthracite reserves were in short supply when coal-burning electricity-generating plants were built at the end of the nineteenth and early twentieth centuries. These plants burned cheaper and more available bituminous coal. New Yorkers staged an early environmental protest against the fouled air that the utility managers could not ignore, so they switched to anthracite coal to appease people while they were awake, but switched back to bituminous while they slept.

We tend to think of air pollution caused by burning coal as a nineteenth-century phenomenon affecting London, Manchester, and Pittsburgh. Yet, only a little over a half-century ago, for four days in early December 1952, a temperature inversion settled over London, trapping a natural white fog so dense that traffic slowed to a crawl and the opera had to be cancelled when the performers could no longer see the conductor. Then coal smoke, also trapped in the temperature inversion, mixed with the fog to produce an unnatural black fog that hugged the ground and cut visibility to less than a foot. Perhaps unbelievably from our vantage point, 4,000 Londoners died from traffic accidents and inhaling sulfur dioxide fumes. Parliament subsequently banned the burning of soft coal in central London, bringing to an end a quaint 700-year-long tradition. In the twenty-first century, Beijing, Shanghai, and other cities in Asia have picked up where London left off. While the results of living in a cloud of polluted air are not as calamitous as in London, nevertheless dwellers in Asian cities suffer from various health impairments.[2]

Coal and the Industrial Revolution

Coal played an important role in England's emergence as the world's greatest seafaring nation and, subsequently, as the world's leading trading nation and colonial power. It also played an important, if not a pivotal, role in bringing about the Industrial Revolution and England's subsequent emergence as the world's greatest industrial power.

At first coal mines were above the River Tyne and narrow downward shafts dug from the mines to the outside world took care of removing water seepage from rain. As the coal seams bent downward, it was only a matter of time before mining took place under the River Tyne and the North Sea. This opened up a whole new peril for the miners: death by drowning. Even if mining did not breach the river or the sea, water was continually seeping in through the ground, threatening to flood the mines, though not necessarily the miners. For many years the chief way to prevent flooding was to have men haul up buckets of water to the mine surface. As mines went deeper into the earth, a vertical shaft was dug where a continuous chain loop with attached buckets brought water from the bottom of the mine to the surface. Water wheels and windmills powered a few of these continuous chain operations, but most were powered by horses. The capital cost in chain loops, along with their attached buckets and the operating cost of feeding and tending to the horses, encouraged the development of bigger mines employing larger numbers of miners in order to produce the greater quantities of coal needed to cover the higher capital and operating costs. Concentrating coal mining in a smaller number of larger operations meant even deeper mines, perversely exacerbating the problem of water removal.

By the 1690s, Britain's principal industry of providing 80 percent of the world's coal was threatened with a watery extinction. The nation's intellectual resources were focused on solving what seemed to be an overwhelming challenge: how to prevent water from flooding the ever-deeper mines. Denis Papin proposed the idea of having a piston inside a cylinder where water at the bottom of the cylinder would be heated to generate steam under the piston that would drive the piston up. Then the heat would be removed, creating a pressure differential between the top and bottom of the piston as the steam condensed to form a vacuum. Atmospheric pressure on top of the piston would drive the piston down and then the water in the bottom of the cylinder would be reheated to generate steam to drive the piston back up. The up-and-down motion of the piston could power a water pump. Thomas Newcomen, who may or may not have heard of Papin's idea, worked ten years to develop a working engine that did just that.

The Newcomen engine was a piston within a cylinder. Steam from burning coal was fed into the cylinder space below the piston, forcing it up. Then a cold-water spray entered the cylinder space and condensed the steam to create a vacuum and a pressure differential between the top and the bottom of the cylinder. Atmospheric pressure on top of the piston would drive the piston down. Simultaneously, an exhaust gate would open, allowing the water from the spray and condensed steam to drain from the cylinder space. Then the exhaust gate would close and steam would reenter the cylinder space. This continual cycle of feeding steam followed by a spray of water into the bottom of the cylinder kept the piston moving up and down. A crossbeam connected the moving piston to a water pump. Mines could now be emptied of water without horses and chain loops with attached buckets, which by this time had reached their limits of effectiveness. By 1725 Newcomen engines were everywhere and had grown to prodigious size, but the alternate heating and cooling of the lower cylinder walls during each cycle of the piston movement made them extremely energy-inefficient. With coal cheap and plentiful, the Newcomen engine had no technological rival for sixty years. As energy-inefficient as Newcomen engines were, they nevertheless saved the English coal-mining industry from a watery grave and enabled England to maintain its preeminence in coal mining for another century.

Thus, coal or, to be more exact, the threat of coal mines filling with water, brought into existence the first industrial fossil-fueled machine that delivered much more power with far greater dependability than wind or water. The fickleness of the wind makes wind power vulnerable and water power is constrained by the capacity of a water wheel to translate falling or moving water into useful power and by the occurrence of droughts. The Newcomen engine had no such limitations.

The building of Newcomen engines required iron and smelting iron consumed charcoal, another contributor to the deforestation of England. The pressure on forests was lifted in 1709 when Abraham Darby, who also advanced the technology of casting pistons and cylinders for Newcomen engines, discovered that coke from coal could substitute for charcoal from wood in smelting iron. It is a bit ironic that coke itself had been discovered some sixty years earlier, in 1642, for brewing beer. London brewers needed a great deal of wood to dry malt. As wood supplies dwindled, they first experimented with coal, but quickly found out that sulfur in coal tainted the malt and, thus, the flavor of the beer. The brewers discovered coke by copying the process of making charcoal from wood, which is essentially baking coal in the absence of oxygen to drive out volatile elements and impurities. Coke is harder than coal, almost pure carbon, and burns at a high temperature without smoke. Malt dried with coke produced a pure, sweet beer.

In 1757 James Watt, an instrument maker for the University of Glasgow, was given an assignment to repair the University's model of the Newcomen engine, which spurred his lifelong interest in steam engines. Watt soon realized that the shortcoming of the Newcomen engine was the energy consumed in reheating the cylinder wall after each injection of cold-water spray. His idea was not to cool the steam in the hot cylinder, but to redirect the steam to another cylinder, or condenser, surrounded by water, where the steam could be condensed without cooling the cylinder wall. Rather than a valve opening to allow a cold spray to condense the steam, a valve opened to allow the expended steam to escape from the cylinder to the condenser. The condensed steam created a vacuum in the bottom of the cylinder, which allowed atmospheric pressure on top of the cylinder to push the piston down. In this way the power cylinder wall would remain hot throughout the operation of the engine, improving its thermal efficiency.

James Watt was assisted by the moral and financial support of Matthew Boulton, a well-known Birmingham manufacturer. After obtaining a patent, the first two steam engines were built in 1776. One pumped water from a coal mine and the other drove air bellows at an iron foundry. The foundry owner, John Wilkenson, invented a new type of lathe to bore cylinders with greater precision, a device that would prove useful for manufacturing steam engines. The final version of the Watt engine came in 1782, when Watt developed the double-acting engine where steam powered the piston in both directions. Steam entering one end of the cylinder drove the piston in one direction, while a valve opening on the other end of the cylinder allowed the spent steam from the previous stroke to exhaust into a condenser. This operation was reversed to drive the piston in the opposite direction. Valves for allowing live steam to enter the cylinder space or spent steam to enter the condenser were opened and shut by the movement of the piston. To further enhance energy efficiency, steam was admitted inside the cylinder only during the first part of the piston stroke, allowing the expansion of the steam to complete the stroke. To further cut heat losses a warm steam jacket surrounded the cylinder and a governor controlled the engine speed. With these enhancements, the Watt steam engine could operate with one-quarter to one-third the energy necessary to operate an equivalent Newcomen engine. Both the Newcomen and Watt engines spurred technological advances in metallurgy to improve metal performance and in manufacturing technology to make cylinders and pistons, lessons not lost on the military for building bigger and better cannons.

Watt's intention was to improve the energy efficiency of the Newcomen engine for pumping water out of mines. Boulton saw Watt's invention as something greater than a more efficient Newcomen engine or a more reliable means of powering his factories than water wheels. Boulton was a visionary who saw the steam engine as a means to harness power for the good of humanity. In Boulton's vision, steam engines would not only drain mines of water but power factories that could be built at any location where coal was nearby. Goods made by machines powered by steam engines would free humans from the curse of drudgery and poverty that had plagued them throughout history.

The world's first industrialized urban center was Manchester, England. The city became the textile center of the world, processing cotton from slave plantations in the United States. Coal was consumed in making iron that went into constructing factory buildings, steam engines, and textile-making machines. Coal also fueled the steam engines that powered the machines and gas given off by heating coal was piped into the factory buildings and burned in lamps to allow round-the-clock operations. All this coal burning smothered Manchester in a thick black blanket of smoke that rivaled pollution in London and, later, Pittsburgh.

The demand for coal from mines near Manchester was so great that narrow shaft seams, which only children could fit into, were brought into use. They had to crawl on their feet and hands dragging heavy sleds of coal behind them like pack animals. Many of these children lived like animals in abandoned portions of mine shafts, separated from their families and daylight. For workers in the Manchester factories, the long hours, the harsh working conditions, the poor pay, the putrid stench of the atmosphere, their appallingly poor health and high death rates, and the breakdown of the family had to be an Orwellian nightmare at its worst, not Boulton's vision at its best. What Friedrich Engels saw in Manchester was recorded in his work *The Condition of the Working Class in England* (1844), which in turn helped Karl Marx shape *The Communist Manifesto* (1848).

Coal and Railroads

The amount of coal a horse can carry on its back is limited, but its carrying capacity can be improved by having it pull a wagon. The dirt roads of the day, with their deep muddy ruts, were impassable for horses hauling heavy wagonloads of coal. A horse's capacity to move cargo jumps by several orders of magnitude when, instead, it pulls a barge on still water. Canals, not roads, could move large volumes of coal to inland destinations. One of the first canals in Britain moved coal to Manchester from nearby coalfields where horses pulled barges from towpaths alongside the canal. This began the canal-building boom in England where, by the early 1800s, canals were used not only to move coal, but all sorts of raw materials and finished goods to and from cities. Since the nature of the terrain and the availability of water restricted canal construction, wagon ways, where horses were harnessed to cargo-laden carriages riding on wooden rails, complemented canals. Rails made horses more effective in moving coal than pulling loaded wagons on muddy, rutted, dirt roads.

Rails also improved coal-mine productivity. It turned out that getting coal out of the mine was as labor-intensive as mining coal. Often human pack animals were responsible for hauling coal on its journey to the mine surface. One human pack animal would pick up a small wagonload from another human pack animal, tow it a bit, and pass it on to still another human pack animal, then walk back to get the next. Lifetimes were spent hauling coal out of mines and, sometimes, living in mines. Mine operators did what they could to make hauling coal easier, but not strictly for altruistic reasons. Installing rails reduced operating costs by having the same work done by fewer human pack animals, thus improving productivity and, incidentally, profitability. Most rails were made of wood, but a few were made of iron.

Because the use of rails had solved the problem of how to move heavy loads, the concept of the railroad was in place when George Stephenson, the father of railways, put together the elements of iron track with a high-pressure Watt's steam engine on a locomotive platform with flanged iron wheels that pulled flanged iron wheeled carriages. Fittingly, the world's first railroad connected a coal town with a river port twenty-six miles away. The Age of the Railroad began in earnest a few years later, in 1830, when a train on its inaugural run between Liverpool and Manchester hit a top speed of an unbelievable thirty-five miles per hour. By 1845 Britain had 2,200 miles of track, a figure that tripled over the next seven years. While the building of railroads meant relatively cheap and fast transportation between any two points in England, the iron for the rails was not cheap.

Coal and Steel

The Iron Age began sometime around 2000 BCE, perhaps in the Caucasus region, where iron first replaced bronze. Iron is harder, more durable, and holds a sharper edge longer than bronze. Iron is also the fourth most abundant element, making up 5 percent of the earth's crust. Iron ore is made up of iron oxides plus varying amounts of silicon, sulfur, manganese, and phosphorus. From its start, smelting iron consisted of heating iron ore mixed with charcoal until the iron oxides began reacting with the carbon in the charcoal to release its oxygen content as carbon monoxide or dioxide. Adding crushed seashells or limestone, called flux, removed impurities in the form of slag, which was separated from the heavier molten iron. This left relatively pure iron, intermixed with bits of charcoal and slag that could then be hammered on an anvil by a blacksmith to remove the remaining cinders, slag, and other impurities. The result of the hammering produced wrought (or "worked") iron with a carbon content between 0.02–0.08 percent. This small amount of carbon, absorbed from the charcoal, made the metal both tough and malleable. Wrought iron was the most commonly produced metal throughout the Iron Age.

By the late Middle Ages, European iron makers had developed the blast furnace, a tall chimney-like structure in which combustion was intensified by a blast of air pumped through alternating layers of charcoal, flux, and iron ore. The medieval ironworkers harnessed water wheels to power bellows to force air through the blast furnaces. Centuries later, this would be one of the first tasks for James Watt's steam engines, in addition to pumping water out of coal mines. The blast of air increased the temperature, which allowed the iron to begin absorbing carbon, thereby lowering its melting point. The product of this high-temperature process was cast iron, with between 3–4.5 percent carbon. Cast iron is hard and brittle, liable to shatter under a heavy blow, and cannot be forged (that is, heated and shaped by hammer blows). The molten cast iron was fed through a system of sand troughs, formed into ingots, which reminded people of a sow suckling a litter of piglets, and became known as pig iron. Pig iron was either cast immediately or allowed to cool and shipped to a foundry as ingots, where it was remelted and poured directly into molds to cast stoves, pots, pans, cannons, cannonballs, and church bells.

These early blast furnaces produced cast iron with great efficiency and less cost than wrought iron. However, the process of transforming cast iron to more useful wrought iron by oxidizing excess carbon out of the pig iron was inefficient and costly. More importantly, what was desired was not wrought iron from cast iron, but steel. Steel is iron with carbon content between 0.2–1.5 percent, higher than wrought iron but lower than cast iron. Crucible steel, named after its manufacturing process, was not only very expensive, but the extent of the oxidation of carbon, and therefore the carbon content, could not be controlled. Regardless of its cost, steel was preferred over wrought iron because it was harder and kept a sharp edge longer (the best swords were made of steel) and was preferred over cast iron because it was more malleable and resistant to shock.

Early rails made from wrought iron were soft and had to be replaced every six to eight weeks along busy stretches of track. Steel, in contrast, is perfect for rails because it is harder than wrought iron and more malleable than cast iron. Steel rails, however, were prohibitively expensive. The man of the hour was Henry Bessemer, who was not responding to the needs of the railroad industry, but the military. Bessemer had invented a new artillery shell that had been used in the Crimean War (1853–1856). The army generals complained that the cast iron cannons of the day could not handle Bessemer's more powerful artillery shell. In response Bessemer developed an improved iron-smelting process that involved blasting compressed air through molten pig iron to allow the oxygen in the air to unite with the excess carbon and form carbon dioxide. Ironically, Bessemer's invention, patented in 1855, was similar to the method of refining steel used by the Chinese in the second century BCE.

In 1856 the first Bessemer converter, large and pear-shaped with holes at the bottom for injecting compressed air, was completed. Other individuals contributed to improving the Bessemer converter by adding manganese to get rid of excess oxygen left in the metal by the compressed air and limestone to get rid of any phosphorus in the iron ore, which made steel excessively brittle. Limestone becomes slag after absorbing phosphorus and other impurities and floats at the top of the converter where it is skimmed off before the steel is poured out. Bessemer converters were batch operations to which iron ore, coke, and limestone were added; within a short period of time, molten steel was on the bottom and slag was floating on the top. After removing the slag, the converter was then emptied of its molten steel and then reloaded to make another batch.

The economies of large-scale production utilizing the Bessemer converter transformed undesired wrought-iron rail at $83 per ton in 1867 to desired steel rail at $32 per ton by 1884. It was not long before the Bessemer process had a technological rival: the open-hearth furnace. The open-hearth furnace, while it took longer, could make larger quantities of steel because raw materials were continuously added and slag and steel continually removed. Moreover, steel could be made with more precise technical specifications and scrap steel could be consumed as feedstock along with iron ore, coal, and limestone. Improvements in the chemical composition of steel had increased the life of steel rails and their weight-carrying capacity several fold by 1900, when the open-hearth furnace had largely replaced the Bessemer converter. Another man of the hour, Andrew Carnegie, organizationally shaped the steel industry and, in so doing, reduced the price of steel rail to $14 per ton by the end on the nineteenth century. Carnegie also introduced the I-shaped steel girder for building skyscrapers, a major addition to steel demand once the Otis elevator was perfected.

By 1960, the basic oxygen furnace had, in its turn, replaced the open-hearth furnace. The basic oxygen furnace is essentially a modification of the original Bessemer converter. The first step is feeding iron ore, coke, and limestone into a furnace with air blasted through the mixture to produce molten iron, which is periodically tapped from the bottom of the furnace while the molten slag is periodically removed from the top. The molten iron then goes into the basic oxygen furnace where steel scrap and more limestone are added, along with a blast of oxygen to produce almost pure liquid steel.

In making steel, coking coal supplies carbon to remove the oxygen in the iron ore and heat to melt the iron. Coking, or metallurgical coal, must support the weight of the heavy contents in a furnace yet be sufficiently permeable for gases to rise to the top and molten steel to sink to the bottom of the furnace. Thus, coals are divided into two types: thermal coal fit only for burning and coking coal fit for steelmaking. The liquid and gaseous byproducts in producing coke from metallurgical or coking coal find their way into a host of products such as synthetic rubber, ink, perfume, food and wood preservatives, plastics, varnish, stains, paints, and tars.[3]

The world's largest steel producers are China (501 million tons, over triple its 2001 production, Japan (119 million tons), the United States (91 million tons), Russia (69 million tons), India (55 million tons), South Korea (54 million tons), Germany (46 million tons), Ukraine (37million tons), Brazil (34 million tons), and Italy (31 million tons). The basic oxygen furnace produces 66 percent of the world's crude steel production—about 1,327 million tons in 2008—incidentally consuming 600 million tons of coal. Most of the remaining steel production is made from a more recent innovation, the electric arc furnace.[4] The raw material for electric arc furnaces is scrap. Incidentally, steel is the most recycled commodity on Earth: fourteen million cars in the United States alone are recycled annually. Whereas 1 ton of steel made from raw materials requires, in round terms, 2 tons of iron ore, 1 ton of coal, and a half ton of limestone; 1 ton of recycled steel needs a bit more than 1 ton of scrap. While coal is absent as a raw material in making steel with the electric arc furnace, an electric arc furnace uses a lot of electricity, as one can imagine, which is mainly generated by burning coal augmented by capturing the waste heat of steelmaking. Thus, coal is consumed directly in making steel with the basic oxygen furnace and indirectly in making steel with the electric arc furnace.

Coal played a vital role in shaping the world as we know it today. Coal was needed as a substitute for wood for producing glass and smelting metals after the forests were cut down. Coal became a major export item for England, spurring the development of the English navy. The challenge posed by flooding coal mines frantically called for a solution—the Newcomen engine—the first industrial power-generating machine not dependent on wind or water. The Newcomen engine spurred further advances in metal and toolmaking and led directly to Watt's steam engine. Watt's steam engine powered the Industrial Revolution with coal, steel, and railroads. Coal, then, is at least partly responsible for England becoming a world sea power, a colonial power, and, after the birth of the Industrial Revolution, the world's first and mightiest industrial power. This lasted for over half a century before being challenged by the emergence of rival centers of industrial power in the United States, Germany, and Japan.

Rise and Fall of King Coal

Though early steam locomotives were fueled by wood, it was not long before they switched to coal. One reason was deforestation; the other was the availability of coal as the most commonly carried commodity. Coal became the sole source of energy for fueling locomotives, which for decades before the automobile age was the sole source of transportation on land other than horses. Robert Fulton invented the first steam-driven riverboat, the *Clermont,* which propelled itself from New York to Albany in 1807. While wood could be burned on riverboats, ocean-going vessels burned coal, a more concentrated form of energy that took up a lot less volume. The famed clipper ships of the waning decades of the nineteenth century marked the final transition from a source of power that was undependable, renewable, and pollution- and cost-free to one that was dependable, nonrenewable, polluting, and not cost-free. Now coal had it all on land and sea. Thomas Edison's first electricity-generating plants were fueled by coal, although hydropower was soon harnessed at Niagara Falls. Coal and hydropower were the principal sources of energy for generating electricity during the first half of the twentieth century.

Coal's share of the energy pie peaked at 60 percent in 1910. Oil, natural gas, and hydropower contributed another 10 percent, and biomass 30 percent. After 1910, things began to change for King Coal. Coal maintained its pre-eminence in passenger transportation until Henry Ford put America, and the world, on gasoline-driven wheels. In 1912, the *Titanic* had 162 coal-fired furnaces fed continuously by 160 stokers working shifts 24/7 shoveling as much as 600 tons of coal per day. This might work well for passenger vessels, but coal-burning warships were constrained in fulfilling their primary mission by the large portion of the crew dedicated to shoveling coal, rather than manning guns, and the amount of space dedicated to holding coal rather than carrying ammunition. Moreover, warships with a heavy cargo of coal moved slowly and their pillars of smoke signaled the enemy as to their whereabouts. Admiral Sir John Fisher, head of the British Navy, spearheaded the transformation from marine boilers powered by coal to oil in the years prior to the First World War. Naysayers scoffed at the idea, but as soon as the obvious advantages of oil over coal were demonstrated in higher speed, greater firepower, and less emissions to betray a vessel's presence, it became a race to dump coal in favor of oil. As ships made the transition from coal to oil, the worldwide network of coal-bunkering stations supplied by coal colliers was converted in tandem to handle oil supplied by tankers (ship's fuel is still referred to as bunkers).

Coal and wood remained the chief sources of energy for cooking until the advent of the electric stove in the 1920s, along with stoves that burned natural gas and liquid propane. About this time, homes began a slow conversion from coal to heating oil and natural gas. Automobiles were taking passengers away from electric trolleys, whose electricity was generated from coal, for inner-city transportation. Intercity railroad passenger train traffic, powered by coal-fueled locomotives, declined as a network of roads sprang into existence. When the fall of King Coal from pre-eminence sped up during and after the Second World War, one individual stood out: John L. Lewis, a former coal miner and president of the United Mine Workers. A contentious personality who had the audacity to defy President Franklin Delano Roosevelt by leading a coal miners' strike during the war, Lewis was instrumental in raising the pay and improving the health and retirement benefits and working conditions for coal miners. As laudable as these well-deserved benefits were, they also increased the price of coal and, in so doing, hastened its demise. Perhaps no better proof of this was Perez Alfonso, a Venezuelan oil minister, who wanted to erect a statue to honor Lewis for boosting the market for Venezuelan oil exports.

The rise in the price of coal from John L. Lewis's success was an added inducement for homeowners to switch from coal, which had to be shoveled into a furnace (from which ashes had to be removed and disposed of) to the much greater convenience of heating oil, propane, and natural gas, which did not require the effort associated with coal. In cooking, the switch was already far advanced from coal to electricity and natural gas and propane.[5] While oil-driven automobiles, buses, and airplanes were diverting people from coal-burning passenger trains, and trucks had taken over local distribution of freight, railroad freight trains still carried the bulk of the nation's intercity freight. Trucks were unable to cut deeply into intercity freight traffic because the road network was relatively undeveloped and better fit for automobiles than trucks. All this changed with the launching of the interstate highway system by President Dwight D. Eisenhower.

A large steam locomotive pulling a loaded freight train burned 1 ton of coal per mile, which required a fulltime fireman to continually shovel coal. Railroads were enormous consumers of coal and railroad executives displayed equally enormous reluctance to abandon steam locomotives when the diesel engine first appeared in the late 1930s. Steam locomotives had become an intimate part of railroading folklore. Distinct in design and operating nuances, they had to be maintained by a dedicated crew that became inseparable from the locomotive, which required a lot of downtime for maintenance and repair.

Railroaders were unwilling to switch from steam to diesel, even though diesel locomotives had inherent advantages. Diesel engines were fuel-efficient because they burned gallons of diesel fuel per mile, not a ton of coal per mile. The diesel engine avoided the inherent energy inefficiency of a steam engine from which the latent heat of vaporization was passed to the atmosphere. In a diesel engine, fuel sprayed into the cylinder space above a piston is ignited by heated compressed air. The expansion of the gases of combustion powers the first downward stroke. After the power stroke, the piston is forced up to expel the exhaust gases, then down to draw in fresh air, then up to compress the air. The heated compressed air ignites another spray of fuel whose expanding gases of combustion powers another downward stroke. Thus, every other downward stroke is a power stroke that, through a crankshaft connected to the other pistons, drives an electricity generator that powers electric motors attached to the engine wheels.

Diesel engines have other advantages as well. They are more reliable because they require less maintenance and repair, both in downtime and cost; less manpower, because no coal has to be shoveled; and less frequent refueling. Steam locomotives of various horsepower have to be built to handle freight trains of different sizes, whereas a number of standard-sized diesel engines can be hooked together to obtain the requisite horsepower. In short, the only reason to keep steam locomotives once diesel engines made their appearance was management's reluctance to change.

The advantages of the diesel engine could no longer be ignored when John L. Lewis's success in improving the lot of coal miners increased the price of coal. The first diesel engines were restricted to moving freight cars around freight yards and were excluded from long intercity runs, the exclusive domain of the steam locomotive. Steam locomotives could persevere as long as all railroad managers agreed to use steam locomotives on intercity freight trains, ensuring equal inefficiency in operations for all. But this holding action could not ignore the competitive threat of a growing volume of trucks gaining access to intercity traffic made possible by the interstate highway system. If any railroad bolted to diesel for hauling intercity freight, then the inherent efficiencies and advantages of diesel locomotion would give that railroad a competitive edge over the others. And that is what happened: one railroad bolted. As soon as one made the switch to diesel for intercity freight trains, it was a race to convert locomotives from coal to oil similar to the race to convert ships from coal to oil. Despite efforts by steam locomotive aficionados and railroad executives to hold the fort, the steam whistle and the chugging locomotive spewing steam, smoke, and at times blazing ashes disappeared within a decade.

Adding to King Coal's woes, electricity-generating plants built after the Second World War were designed to run on oil, natural gas, and nuclear power in addition to coal and hydro. King Coal was no longer king in transportation, electricity generation, heating houses and commercial buildings, and home cooking. By 1965, its share of the energy pie was down to a still respectable 39 percent and declined to 30 percent in 1970 and remained around 25–29 percent until recent years when its share expanded to 30 percent.

TYPES OF COAL

Aside from peat, a precursor to coal, there are four types of coal. The lowest quality of coal and the largest portion of the world's coal reserves is lignite, a geologically young, soft, brownish-black coal, some of which retains the texture of the original wood. Of all coals, it has the lowest carbon content, 25–35 percent, and the lowest heat content, 4,000–8,300 British thermal units (Btus) per pound. The next step up is sub-bituminous coal, a dull black coal with a carbon content of 35–45 percent and heat content 8,300–13,000 Btus per pound. Both lignite and sub-bituminous coals, known as soft coals, are primarily thermal coals for generating electricity. Some sub-bituminous coals have lower sulfur content than bituminous coal, an environmental advantage.

Next are the hard coals, bituminous and anthracite. Bituminous is superior to soft coal in terms of carbon content, 45–86 percent, and energy content, 10,500–15,500 Btus per pound. Bituminous coal is the most plentiful form of coal in the United States and is used both to generate electricity (thermal coal) and, if it has the right properties, as coking or metallurgical coke for steel production. Anthracite coal has the highest carbon content, 86–98 percent, and a heat content of nearly 15,000 Btus per pound. Anthracite coal was closely associated with home heating because it burned nearly smokeless. As desirable as anthracite is, it is also scarce. In the United States, anthracite is found in only eleven counties in northeastern Pennsylvania and is a largely exhausted resource.

COAL MINING

Coal mines have historically been subterranean regions where accidents and black lung have taken their toll. Mining coal in the twenty-first century is an activity carried out differently than it was in the past. In developed nations, no gangs of men swing pickaxes to remove the over- and underburden of rock to gain access to the coal, then again to chip out the coal. No gangs of men shovel the rock or coal into small wagons or carts for the trip to the surface. Now the most popular way of removing coal is continuous mining machines with large, rotating, drum-shaped cutting heads studded with carbide-tipped teeth that rip into a seam of coal. Large gathering arms scoop the coal directly into a built-in conveyor for loading into shuttle cars or a conveyor for the trip to the surface. Continuous cutters ripping and grinding their way through coal seams can do in minutes what gangs of miners with pickaxes and shovels took days to accomplish.

The next most popular method for removing is a machine resembling an oversized chain saw that cuts out a section of coal in preparation for blasting to allow for expansion. Holes are then drilled for explosives that blast large chunks of coal loose from the seam. Loaders scoop up the coal into conveyors that fill shuttle cars to haul the coal out through the shaft. For both methods of mining, long rods or roof bolts are driven into the roof of the mine to bind layers of weak strata into a single layer strong enough to support its own weight. If necessary, braces are used for additional support. Wood is favored because it makes a sharp cracking sound if the roof begins to weaken.

An increasingly popular and efficient means of mining introduced into the United States from Europe in the 1950s is longwall mining where a rotating shear moves back and forth in a continuous, smooth motion for several hundred feet across the face or wall of a block of coal. The cut coal drops into a conveyor and is removed from the mine. Some of the rock on top of the coal also collapses, which is then removed to the surface or piled in areas where the coal has been removed. The main supports for the rooms created by longwall mining are pillars of solid coal, which are the last to be mined before a mine is abandoned.

Regardless of the type of mining technology employed, mine shafts for transporting miners and coal either slope down to coal beds that are not too deeply located in the earth or are vertical to reach beds of coal more than 2,000 feet beneath the surface. Huge ventilation fans on the surface pump air through the mineshafts to reduce the amount of coal dust in the air, prevent the accumulation of dangerous gases, and ensure a supply of fresh air for the miners.

In recent decades, surface mining has gained prominence over subterranean mining. In the western part of the United States, 75 percent of the coal produced is obtained from surface mines with coal deposits up to 100 hundred feet thick. Surface mining also occurs in Appalachia. Surface mines produce 60 percent of the coal mined in the United States, while the remaining 40 percent comes from underground coal mines located primarily in Appalachia. Although there are large open-pit mines in other parts of the world, such as Australia and Indonesia, globally speaking about two-thirds of coal comes from underground mines.

A few utility plants are located at the mouths of mines, but most coal is loaded on barges and railroad cars for transport to electricity-generating plants or export ports. In the United States, about 60 percent of the coal mined is moved by railroad to the consumer, often in unit trains of a hundred automatically unloading coal cars, each holding 100 tons of coal, or 10,000 tons of coal in a single trainload. Coal is unloaded by hoppers in the bottom of coal cars that open to drop the coal onto a conveyor belt located below the rails or by a rotating mechanism that empties 100 tons of coal by turning the coal cars upside down as though they were toys. Coal is still a major revenue generator for railroads around the world. Coal in the United States not moved by rail is primarily moved by barge on 25,000 miles of inland waterways. One unconventional way to move coal is to pipeline pulverized coal mixed with water from a coal mine to a power station, where the water is decanted and the pulverized coal is fed directly into a boiler.

After mining, coal is processed to ensure a uniform size and washed to reduce its ash and sulfur content. Washing consists of floating the coal across a tank of water containing magnetite for the correct specific gravity. Heavier rock and other impurities sink to the bottom and are removed as waste. Washing reduces the ash and pyretic sulfur-iron compounds clinging to the surface of the coal, but not the sulfur chemically bonded within the coal. Washing can also reduce carbon dioxide emissions by 5 percent. Magnetite clinging to the coal after washing is separated with a spray of water and recycled. Coal is then shipped by rail or barge to power plants. Some power plants run off a single source of coal while others buy various grades of coal that are mixed together before burning in order to obtain optimal results in heat generation, pollution emissions, and cost control.

Coal-mining operations are highly regulated in the developed world. In the United States, a company must comply with hundreds of laws and thousands of regulations, many of which have to do with the safety and health of the miners and the impact of coal mining on the environment. Legal hurdles may require ten years before a new mine can be developed. A mining company must provide detailed information about how the coal will be mined, the precautions taken to protect the health and safety of the miners, and the mine's impact on the environment. For surface mining, the existing condition of the land must be carefully documented to make sure that reclamation requirements have been successfully fulfilled. Other legal requirements cover archaeological and historical preservation, protection and conservation of endangered species, special provisions to protect fish and wildlife, forest and rangeland, wild and scenic river views, water purity, and noise abatement.

In surface or strip mining, specially designed draglines, wheel excavators, and large shovels strip the overburden to expose the coal seam, which can cover the entire top of an Appalachian mountain. Coal is loaded into huge specially designed trucks by large mechanical shovels for shipment to a coal-burning utility or to awaiting railroad cars or barges. Surface mining has lower operating and capital costs and provides a safer and healthier environment for the workers than underground mining. After the coal is removed, the overburden is replaced and replanted with plant life to restore the land as closely as possible to its original state. Reclaimed land can also be transformed into farmland, recreational areas, or residential or commercial development, as permitted by the regulators.

Critics of surface mining point out the damage done to the landscape when the overburden removed from the top of a mountain or hill is dumped into nearby valleys, called "valley fill." In addition to the destruction of the landscape and vegetation, valley fills become dams creating contaminated ponds of acid runoff from sulfur-bearing rocks and heavy metals such as copper, lead, mercury, and arsenic exposed by coal mining. They also object to the dust and noise of strip-mining operations and "fly-rocks" raining down on those unfortunately residing nearby. The scars of surface mining are clear from the air. Residents in West Virginia are split between those who support the economic benefits of surface coal mining and those who want to transform West Virginia into a recreational destination for tourists.[6] Another problem is abandoned underground mines, which eventually fill with water. The water can range from being nearly fit for drinking to containing dangerously high concentrations of acids and metallic compounds that may end up contaminating ground and drinking water.

Table 4.1

Employment, Productivity, and Safety

	Employment (2000)	Miners per Million Tons Output	Deaths	Deaths per Million Tons Output
Australia	18	76	4	0.02
United States	77	96	38	0.05
United Kingdom	8	241	4	0.05
South Africa	54	298	30	0.17
Poland	158	1,561	28	0.28
India	456	2,171	100	0.48
Russia	197	1,195	137	0.83
China	5,000	5,501	5,786	6.36

Of course, the record also shows that there are large established companies mindful of their legal obligations to restore the landscape and protect the environment. There are instances of reclamation carried out so effectively that, with the passage of time, there is no apparent evidence that strip-mining had ever taken place. Aside from corporate ethics, there are sound business reasons for being a responsible corporate citizen such as the desire to remain in business for decades to come. For these companies, the extra costs in protecting the health and safety of the miners and safeguarding the environment generate huge payoffs by allowing them to remain in business over the long haul. Private ownership is a right granted by governments on the basis that the conduct of business is better handled by businesspeople than government bureaucrats. If in reality, or if in the perception of the electorate, the supposed benefits of private ownership are not being achieved, then private ownership itself is threatened.

There has been environmental degradation, but much of this lies with fly-by-night companies that fold without meeting their light-of-day responsibilities. While critics of coal extraction in developed nations abound, the developing nations, most notably China and India, seem to exist on another planet. Coal mining, particularly in the tens of thousands of small mines, violates elemental concerns over health and safety of the workers and the environment. No one in those countries seems to care about spontaneous combustion of coal-mining residues that burn on forever or drinking water and agricultural lands permanently contaminated with poisonous metal compounds.

Employment of coal miners has changed drastically in recent decades as machines have replaced labor. Although there are 7 million coal miners in the world, 5 million are in China and another half million are in India, where the use of picks and shovels is the dominant coal-mining technique. Table 4.1 shows employment, productivity, and safety in terms of the number of miners per million tons of output, the number of miners' deaths, and deaths in terms of a million tons of output for 2000.[7] The table shows the enormous disparity in worker productivity and mortality rates between the developed and developing worlds. More recent data suggest that official coal mining deaths in China may be closer to 4,000, but there is also an element of underreporting from remote areas that suggest that the death rate may be higher than what the statistics show. Note that coal mining in the United Kingdom, where it all began, is now a faint vestige of its former vigor.

Needless to say, the lowest fatality rates occur in nations where there is the strongest commitment to health and safety standards for miners and for workers in general. China has the most abysmal safety record, and that may be a gross understatement. Most casualties are associated with small mines employing women and children, not the large state-owned mines. Methane explosions from lack of proper ventilation and gas monitoring are responsible for half of the deaths. These figures reflect mine mishaps, not deaths from health impairment from mining. A nonfatal occupational risk for miners and for many other industrial workers is loss of hearing. For coal miners, loss of hearing, caused by explosives used to dislodge coal and machinery noise in close quarters, occurs slowly and often without the miner's awareness. With regard to fatal occupational risks, the most common disease is pneumoconiosis, commonly known as black lung disease. Black lung disease has dropped precipitously for mines with ample ventilation to reduce coal dust, but still remains a problem in China and India and other nations where relatively little is invested in protecting the workers' health. China's terrible record in protecting miners extends to the end users. Drying chilies with coal contaminated with arsenic was responsible for thousands of cases of arsenic poisoning. Drying corn with coal contaminated with fluorine caused millions to suffer from dental and skeletal fluorosis.

COAL IN THE TWENTY-FIRST CENTURY

Coal's retreat in relative standing among other energy sources ended in 2000. Coal is here to stay and is gaining ground in absolute and relative terms. Despite criticisms leveled against coal, it does have virtues that cannot be ignored such as being:

- abundant, frequently reserves are measured in hundreds of years;
- secure, in that coal is available in sufficient quantities without the need for large-scale imports for most coal-consuming nations;
- safe (does not explode like natural gas, but of course mine safety is an issue);
- nonpolluting of water resources as oil spills are (although there are other adverse environmental consequences of mining and burning coal);
- cost-effective, by far the cheapest source of energy.

As seen in Figure 4.1, the volume of coal production leveled out in the 1990s but is heading upward again. The top line is coal mined in physical tons and the bottom line is coal production expressed in terms of the equivalent amount of oil that would have to be burned to match the energy released by burning coal. As the figure shows, close to 2 short tons of coal have to be burned to obtain the same energy release as burning 1 metric ton of oil.[8]

Figure 4.1 also shows the relative contribution that coal makes in satisfying world energy demand for commercial sources, excluding biomass. Since 1981, the percentage of coal's share in satisfying energy needs had been slowly eroding until 2001 when there was a resurgence in coal consumption and in its share of the energy pie. This trend is expected to continue from coal-fired electricity generation capacity being added all over the world but particularly in the United States, China, and India. However, there has been a sharp decline in ordering new coal-fired electricity-generating capacity in the United States because of the risk of a cap and trade program being imposed by the Obama administration. The global economic recession starting in 2008 also affects utility plans to add capacity. Regardless of the situation in the United States, China and India will remain principal drivers of the world coal business.

Figure 4.1 **Global Coal Production and Percent Contribution to Global Energy**

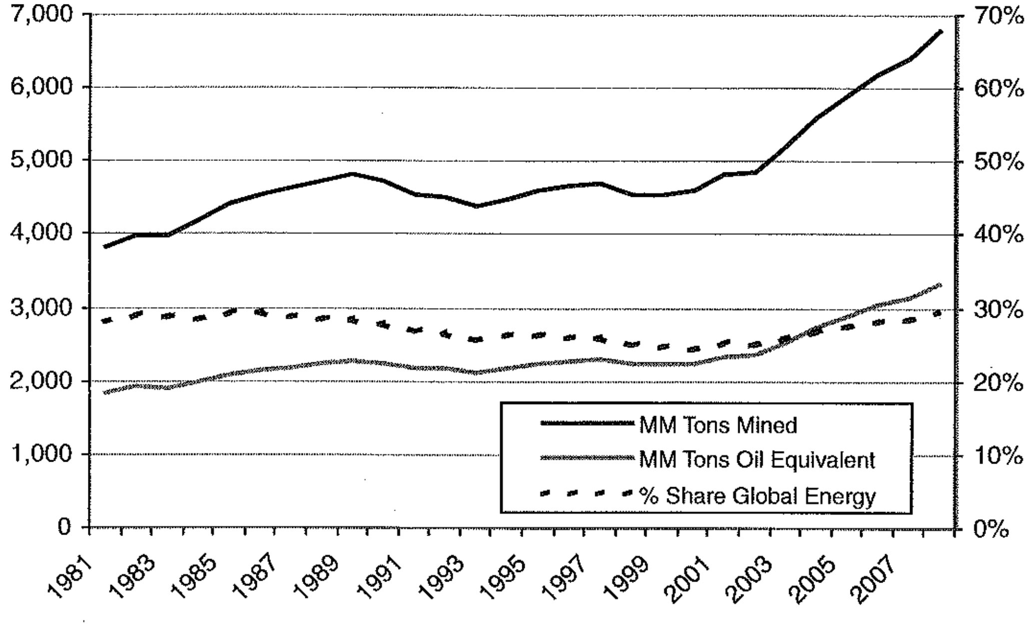
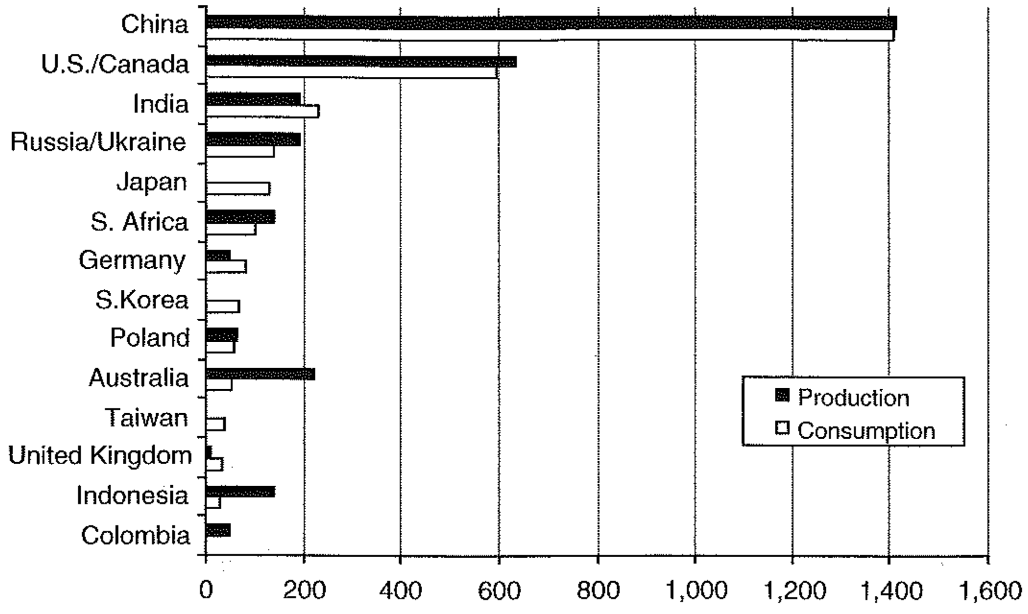


Figure 4.2 shows the world's largest consumers and producers of coal in 2008 in terms of millions of tons oil equivalent. China is the world's largest consumer and producer of coal and both exports and imports coal. China suffers from a poorly developed internal logistics system. Movement from inland distributions to coastline population centers relies heavily on China's river systems. Movement of goods and commodities along China's long coastline, where a number of its principal population centers are located, is by water rather than by land. As a substitute for moving commodities along its coastline, China selectively exports and imports. China imports thermal coal to utilities located on its coast from Australia and Indonesia and exports thermal coal to neighboring countries such as North and South Korea and Japan. By becoming a major world steel producer, China has become a major importer of metallurgical or coking coal. The steam locomotive has not entirely gone the way of dinosaurs. China, India, and South Africa still rely on steam locomotives to move coal.

The relative importance of the United States, along with Canada and China, as consumers and producers of coal can be seen by the huge step down to the third largest consumer and producer, India. Thermal and metallurgical or coking coal are two distinct markets. It is possible for a large bulk carrier to move thermal coal from Australia to Europe and return with a cargo of metallurgical coal from the United States or South Africa to Japan. The largest steam and coking coal exporters in 2008 were Australia (252 million tons), Indonesia (203 million tons), Russia (101 million

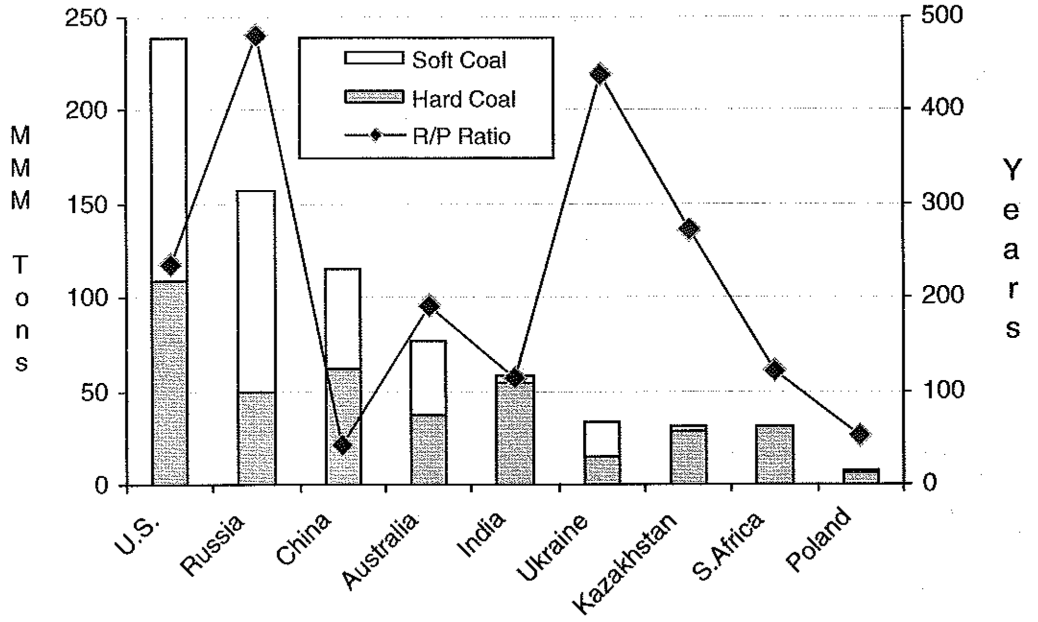
Figure 4.2 **World's Leading Producers and Consumers of Coal** (MM Tons Oil Equivalent) **in 2008**



tons), Colombia (74 million tons), United States (74 million tons), South Africa (62 million tons), and China (47 million tons). The largest importers were Japan (186 million tons), South Korea (100 million tons), Taiwan (66 million tons), India (60 million tons), Germany (46 million tons), China (46 million tons), and United Kingdom (44 million tons). Japan, South Korea, and Taiwan view coal as a means of reducing their reliance on Middle East oil. The United Kingdom, once the world's largest exporter of coal, now imports a large share of its coal needs. Both the United Kingdom and Germany have been phasing out the large subsidies paid to keep its domestic coal-producing industry alive in favor of far cheaper imports.

South Africa has abundant coal resources and limited oil resources, and oil-exporting nations were reluctant to trade because of its past apartheid policies. As a consequence, South Africa became a world leader in producing petroleum products (synthetic fuels) and chemicals from coal. The Fischer-Tropsch process, dating back to the 1920s, transforms low-quality coal to high-grade petroleum fuels plus other products.[8] The Germans relied on this technology to make gasoline from its plenteous supplies of coal during the Second World War to compensate for not having indigenous oil resources to run its war machine. These plants were the highest priority targets during Allied bombing of Nazi Germany. The South African plants have been producing 130,000 barrels per day of a mix of 20–30 percent naphtha and 70–80 percent diesel, kerosene, and fuel oil since 1955. About 0.4 tons of coal are consumed for every barrel of oil produced with an overall energy efficiency of 40 percent (60 percent of the energy content of the coal is consumed in transforming coal to liquids). Coal is first gasified to yield a mixture of hydrogen and carbon monoxide, which, after passing through iron or cobalt catalysts, is transformed into methane, synthetic gasoline or diesel fuel, waxes, and alcohols, with water and carbon dioxide as byproducts. Synthetic fuels from coal are higher in quality than those made from oil. For instance, diesel fuel made by the Fischer-Tropsch process has reduced nitrous oxides, hydrocarbons, and carbon monoxide emissions with little or no particulate emissions compared to oil-based diesel fuels.[9]

Figure 4.3 **Known Coal Reserves (Billion Tons) and R/P Ratio** (Years)

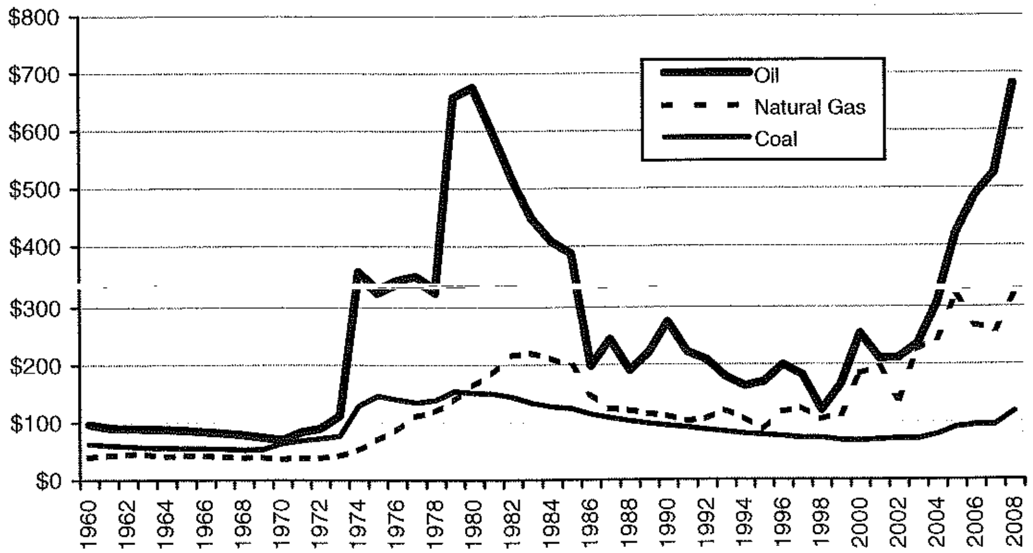


China is building a coal-to-liquids plant in Inner Mongolia that will produce 20,000 barrels per day of motor vehicle fuel plus other oil products with a planned expansion to 100,000 bpd. The process is a direct liquefaction process transforming coal to a solvent at a high temperature and pressure and then followed by a more complex chemistry to produce 20–30 percent naphtha and 70–80 percent diesel fuel and liquefied petroleum gas. The process is more efficient and uses 0.3–0.4 tons of coal per barrel of oil produced. If successful, other coal-to-liquid plants will be built. One adverse environmental aspect of coal-to-liquid technology is a large emission of carbon dioxide during the production process amounting to about 0.6 tons of carbon dioxide for every barrel of oil.[10]

Unlike oil, where the world's total proven reserves divided by current consumption equal only forty years, over a century (120 years) would be required for current consumption to eat away at proven coal reserves. The reserve to production (R/P) ratio has to be handled gingerly as we have a knack for discovering new reserves. (Theodore Roosevelt estimated that oil reserves would be exhausted in twenty years, given consumption and known reserves in the 1910s.) Moreover, reserves are made up of known reserves plus estimates of probable reserves, and as such are subject to error. Some criticize R/P ratios because they are based on current, not future, consumption and to that extent overestimate the life of existing reserves. On the other hand, they do not take into account future discoveries and so underestimate the life of existing reserves. Unlike oil, there is no active ongoing search for new coal reserves, which means that coal reserves could be substantially upgraded. Figure 4.3 shows the world's largest known coal reserves in terms of size, ranked by how long they will last at the present rate of consumption.

The United States has the world's largest reserves of coal of 238 billion tons with a R/P ratio of 234 years, whereas Russia has 157 billion tons with a R/P of 481 years. The world's largest

Figure 4.4 **U.S. $/Ton Oil, Natural Gas, and Coal Prices** (Constant 2008 $)



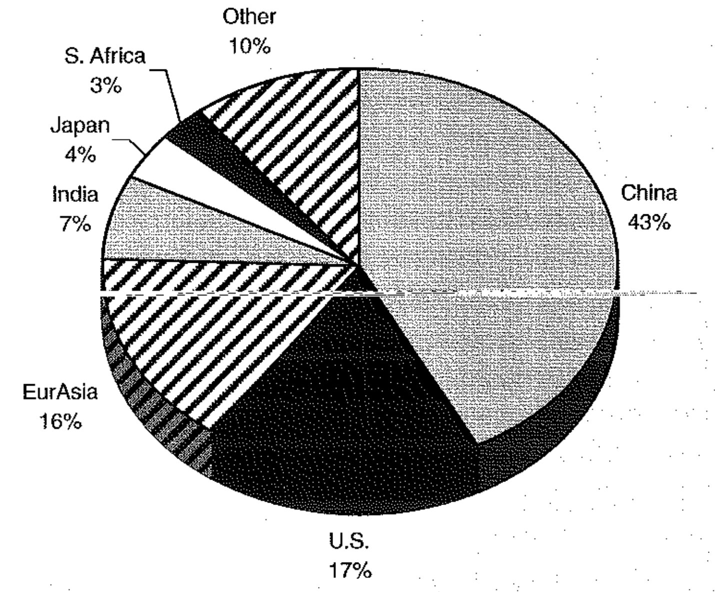
consumer of coal, China, has reserves of 115 billion tons with a R/P of only 41 years. Of course, the nature of the reserves does not reflect the type of coal actually being mined. As previously mentioned, soft coals are lignite and sub-bituminous and hard coals are bituminous and anthracite. Premium bituminous coal for making coking coal for steel production is found in Australia, the United States, Canada, and South Africa. Significant portions of reserves in Russia, Ukraine, and China are soft coals, generally perceived to be greater pollutants than hard coals. But there are exceptions. India has only hard coal, but of poor quality in terms of heat, ash, and sulfur content. Both China and India burn coal with virtually no environmental safeguards. Ash, the residue of burning, is released to the atmosphere in the form of airborne particulates (soot) and sulfur is released as sulfur dioxide gas.

The United States's enormous reserves of coal enhance the nation's energy self-sufficiency. Its reserves can last nearly 250 years at the present rate of production. The coal situation in the United States is quite unlike oil where two-thirds is imported, and the R/P ratio on domestic oil is only twelve years. Some of the imported oil is from volatile and unstable and, at times, distinctly unfriendly nations. Coal does not demand an enormous overseas military presence to ensure security of supply. Moreover, coal has other virtues: it is cheap and its price is much more stable compared to oil and natural gas as shown in Figure 4.4.[11]

A picture is worth a thousand words. Since the oil crisis of 1973, coal prices have been much lower than oil and natural gas (for the most part) and much more stable. But a picture does not include everything. What cannot be seen is that coal is a reliable domestic source of energy not subject to the whims of oil potentates.

The picture for Europe would reflect higher mining costs for coal than in the United States. The picture for Japan would reflect higher shipping costs since all coal must be imported. The picture for China and India would reflect lower mining costs in terms of lack of investment in mechanization, near-slave wages for miners, with little spent for personal safeguards for their health and safety and for environmental safeguards to protect the population from pollution. This heavy reliance on low-cost coal affects the competitive position of China and India in world trade since the cost of energy is an element in the price of exported goods.

Figure 4.5 **Percent Share World Coal Consumption by Nation in 2008**



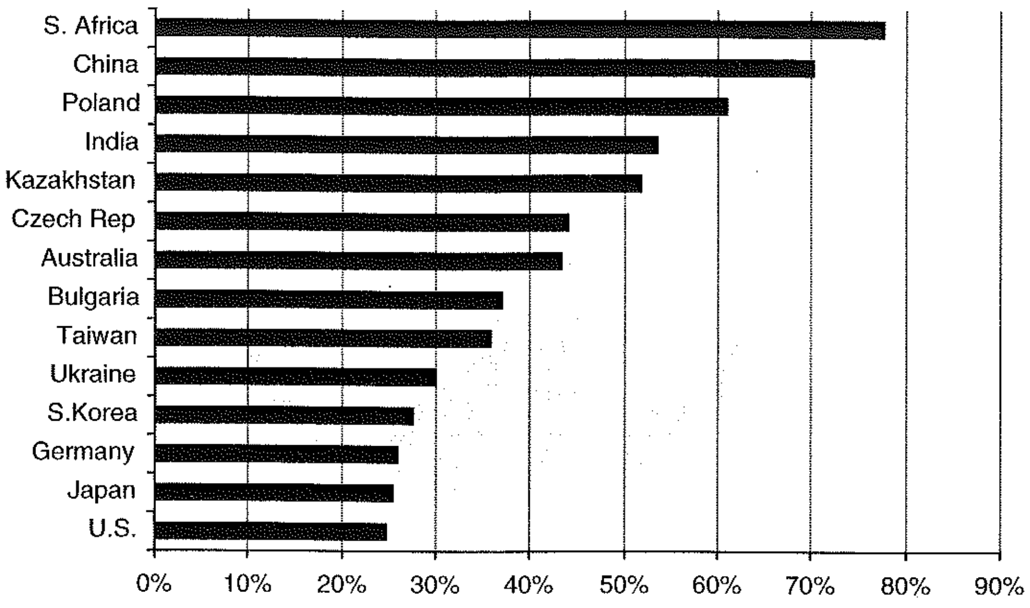
ROLE OF COAL AMONG THE MAJOR CONSUMERS

The primary use of coal is in electricity generation followed by steel production. Electricity and cleaner-burning heating oil and natural gas heat homes and cook food in developed nations, but coal (and biomass) are still burned for heating homes and cooking food in China and India. The six leading consumers of coal in 2008 were China, the United States, Europe, Russia and Central Asia (EurAsia), India, Japan, and South Africa as shown in Figure 4.5.

As seen in Figure 4.6, the nations with the greatest dependence on coal (over 50 percent) as an energy source are South Africa, China, Poland, India, and Kazakhstan. In 2000, China's coal consumption temporarily dipped as a result of an order from Beijing to close 50,000 small and inefficient mines for safety and economic reasons. The official data released by China on coal consumption presumed that these mines were closed and no longer producing coal. However, just as King Edward I's ban on burning coal in London was not heeded on the streets of London, it turned out that orders emanating from Beijing were not carried out in the provinces. China, without much in reserves of oil and natural gas, depends on coal as an industrial and residential fuel. Without replacement energy, thousands of small inefficient mines could not be closed, although the official statistics presumed that they were.

The failure of thousands of mines to close when ordered to do so also underscores a critical problem in China; its relentless pursuit of economic development is driving energy consumption through the roof. As much as China desires to diversify its energy sources to reduce the nation's

Figure 4.6 **Percent Dependence of Various Nations on Coal**



reliance on coal, it cannot cut coal consumption without suffering severe economic dislocation. As long as China's economic locomotive speeds faster and faster, coal will play an increasingly important role. China's building of hydropower dams and nuclear power plants will cut into coal consumption, but it will be years before their construction is completed.

On the surface, India is in a better position than China because it is less dependent on coal, although its dependence has been slowly climbing from its low point in 1999. From another perspective, India is in a worse position than China. China has an enormous trade surplus that is supporting the development of alternative sources of energy to coal (natural gas, hydro and nuclear power). India suffers from a negative trade balance and is less able to finance development of alternative energy sources or the import of energy such as natural gas. Thus, greater coal consumption, and possibly greater biomass consumption, may be the primary solution to India's growing energy needs rather than importing clean energy such as natural gas—unless energy providers are willing to accept rupees rather than dollars (one liquefied natural gas import scheme calls for rupee payments). Until there is a slowing of their economic locomotives, coal consumption in India and China will continue to expand both in volume and relative share of the energy pie.

King Coal was being unceremoniously dumped in the United States until the oil crisis in 1973 when coal's share of the energy pie fell to a low point of 18 percent. Even so, coal consumption in absolute terms was still rising slowly. Consumption accelerated after the oil crisis as coal found a ready market to replace oil as a fuel for electricity generation, rising to 24 percent of the energy pie in 1985. A slowing in the growth of electricity consumption and the collapse in oil prices in 1985 removed the financial incentive for building large coal plants. For environmental and economic reasons, there was a major shift in favor of building lower capital cost and smaller natural gas-burning electricity-generating plants, which better fit growth patterns.

Since 1985 coal's share of the energy pie has been relatively constant, yet coal consumption continued to increase in line with total energy consumption. This is quite remarkable considering

that nearly all new electricity-generating plants in the United States in the 1990s and early 2000s were fueled by natural gas. With virtually no coal-burning plants built during these years, the only conclusion one can reach in examining the upward trend in consumption is that existing coal plants were operating at higher average utilization rates. This near-total reliance on natural gas during the almost twenty-year natural gas "bubble" of low natural gas prices burst in 2003 when demand finally outstripped supply. As natural gas prices rose to record levels, utilities took a second look at the idea of constructing coal-fired plants, and began ordering a number of new plants. With the building of these plants, coal's share of the energy pie slowly began to increase. Despite the bad publicity coal receives in the United States, it is still viewed as a national asset, plentiful, cheap, and secure, providing half the nation's electricity. Existing coal-fired electricity-generation plants and new ones being built will keep the coal industry a viable business and ensure the employment of tens of thousands of coal miners for a long time to come even in the face of a costly carbon cap and trade program. It will take decades to replace coal-fired plants with clean-burning alternatives and at a great cost. All that a cap and trade program will do is reduce the future number of coal-fired plants with the consumer bearing a higher cost of electricity.

Europe is one place in the world where coal is in retreat, both in relative and absolute terms. Coal consumption was slowly declining and its share of the energy pie was dropping fast until the oil crisis in 1973. Then coal's share leveled off as coal consumption increased to displace oil in electricity generation. Since 1985, it has been downhill for coal being replaced by nuclear power and natural gas. Nuclear power has been aggressively pursued in Europe, particularly in France. A natural gas pipeline grid has been built connecting the gas fields of Russia, the Netherlands, North Sea, Algeria, and Libya, with customers throughout Europe. Nuclear power and natural gas have largely displaced coal and oil for electricity generation and as an industrial fuel. Moreover, the Europeans are intent on ensuring that the role for coal is not resurrected by relying on wind and natural gas to meet incremental electricity needs. The interruptions of Russian gas supplies in 2006 and 2008/09 as a result of a pricing dispute with the Ukraine have tempered the willingness of Europeans to rely on Russian natural gas and they have inaugurated a program to diversify natural gas supplies.

Coal mining is a heavily subsidized industry in parts of Europe. Given an average import price of $40 per ton range, the average subsidy per ton of coal produced in Germany is estimated to be $144 per ton and $75 in Spain. France has an even higher subsidy rate, but its coal production is small. Subsidizing industry has been losing its allure for the last few decades. The United Kingdom has done away with coal subsidies by closing its most inefficient and heavily subsidized mines and significantly increasing the productivity of those remaining. Moreover, UK coal must compete with other forms of energy after the UK privatized its electricity-generating industry, including imported coal. UK coal production is a shadow of its former self, and German coal production is in a long-term decline. Both nations import a large portion of their coal needs. While European coal production is in a long-term slow decline, it supports steelmaking and still-existent coal-burning electricity-generation plants.

Before the fall of communism in 1989, coal consumption in Russia was fairly steady, although nuclear power and natural gas were eroding coal's share of the energy pie. After 1989, the reduction in coal consumption was primarily caused by the fall in electricity demand that accompanied the collapse of the Russian economy. During the 1990s, oil consumption for electricity generation was sharply curtailed to make room for exports, slowing the decline in the role of coal. Looking into the future, the primary beneficiary for satisfying incremental demand for electricity will be natural gas. The organizational and financial restructuring of coal mines in Russia, the Ukraine, Kazakhstan, and Poland have resulted in the closing of the most inefficient and heavily subsidized mines and enhanced productivity of those remaining. The restructuring has basically stabilized aggregate coal production for these nations.

Japan does not look at coal as a pollutant as much as a means to diversify energy sources to reduce its reliance on oil, most of which comes from the Middle East. Consumption of coal is increasing in recent years as a result of building more coal-fired electricity-generating plants. In addition to thermal coal for generating electricity, Japan, as a major world steel producer, also imports coking or metallurgical coal. As in North America and Europe, coal is burned in an environmentally sound manner in Japan. The role of coal in Japan was stable at around a 17–18 percent share of the energy pie but has recently increased to 25 percent. Coal is having a bit of a revival in Asia, besides China, India, and Japan, as a means of energy diversification. South Korea, Thailand, Malaysia, and the Philippines have built coal-fired electricity-generating plants.

CASE AGAINST COAL

The case against coal can be put simply, in one word—pollution. Pollution from lower-grade coals, whether soft or hard, is greater than higher-grade coals in terms of the quantities of ash and nitrous and sulfur oxides released during combustion. Also, a greater quantity of lower-grade coals has to be burned for the same release of energy. Airborne, nitrous oxides contribute to smog and sulfur oxide droplets collect on the upper surfaces of clouds, enhancing their reflectivity. This reduces the amount of sunshine reaching the earth and, paradoxically, is a counter-pollution measure to carbon dioxide that reduces the amount of heat that can escape from the atmosphere. Eventually, sulfur and nitrous oxides return to Earth in the form of acid rain, which harms plant and marine life and erodes stone buildings and statues. Mercury, arsenic, selenium, and other heavy metals are also released when coal is burned. Surface mining destroys the landscape and, along with residues from underground mining, affects water supplies.

Abandoned coal mines can catch fire and burn underground. Once on fire, there is little that can be done to stop coal-mine fires other than entering the mine with earth-moving equipment and taking away the source of the fire: the remaining coal in the mine. In 1962, burning trash near the mouth of a mine near Centralia, Pennsylvania, started an underground inferno that has been spreading ever since despite several attempts to extinguish it. The fire is burning at a depth of 300 feet beneath the surface and giving off enough heat to bake the surface, threatening to cremate bodies buried in the local cemetery. There is also venting of poisonous gases and opening up of holes large enough to swallow automobiles. It is thought that the fire will continue for another 250 years in an eight-mile area encompassing 3,700 acres before the fire runs out of fuel. Centralia has been largely abandoned except for a few diehards.[12]

Coal fires are not all the fault of men. Lightning igniting brush fires can cause spontaneous combustion of coal exposed to the atmosphere. Burning Mountain in Australia has been burning for an estimated 6,000 years. Most of the thousands of coal mine fires that threaten towns and roads, poison the air and soil, and worsen global warming are, however, inadvertently started by man. The estimate of the amount of coal burned each year in mine fires in China varies between 20 and 200 million tons per year; the high-end estimate is an appreciable fraction of China's total coal consumption. As bad as China is, India is even worse. Rising surface temperatures and toxic byproducts in the groundwater and soil have turned formerly populated areas into uninhabitable wastelands.

CLEAN-COAL TECHNOLOGIES

Coal is indispensable in the generation of electricity. A great deal of corporate- and government-sponsored research is dedicated to producing a clean coal, termed an oxymoron by critics. Modern coal-burning utility plants remove 99 percent of the ash produced as residue falling to the bottom of the combustion chamber and by electrostatic precipitators that remove ash from the flue gas. A flue gas desulfurization unit sprays a mixture of limestone and water into flue gas to reduce sulfur oxide emissions by 90–97 percent. Sulfur oxides chemically combine with the limestone to form calcium sulfate, or gypsum.[13] Sulfur emissions have fallen 2–3 percent per year in the United States, despite rising coal consumption, through greater use of scrubbers to remove sulfur and greater reliance on low-sulfur coal.

After mining and washing, coal is transported by train, barge, or truck and piled outside the electricity-generating plant until needed. A conveyor then moves the coal into the plant where it is first crushed and pulverized into a fine powder before being blown by powerful fans into the combustion chamber of a boiler in a conventional plant to be burned at 1,300°C–1,400°C, which transforms water in tubes lining the boiler to high-pressure steam that is fed to a turbine.

In addition to a conventional boiler, a fluidized bed combustion chamber can burn pulverized coal of any quality including coal with a high ash and sulfur content. The pulverized coal is burned suspended in a gas flow with heated particles of limestone at half the temperature (1,500°F) of a conventional coal-fired boiler. At this lower temperature, about 90 percent of the sulfur dioxide can be removed by the limestone absorbing the sulfur dioxide to form calcium sulfate or gypsum without the use of an expensive scrubber. In a conventional plant, water tubes in the combustion chamber generate steam to drive a steam turbine. In a fluidized bed combustion plant, both steam and hot combustion gases drive two types of turbines. Steam from the boiler tubes is fed into a conventional steam turbine. Hot combustion gas, after ash and gypsum have been removed, is fed into a gas turbine. Both the steam and gas turbines power electricity generators. The spent combustion gases from the gas turbine pass through a heat exchanger to further warm condensed water from the steam condenser returning to the combustion chamber. The two advantages to a fluidized bed combustion plant are an enhanced energy efficiency of 45 percent and a reduction of about 40–75 percent in nitrous oxide emissions from the lower temperature of combustion. Fluidized bed combustion chambers normally operate at atmospheric pressure, but one currently being developed would operate at a considerably higher pressure.

The first thermal plants built around 1900 were only 5 percent energy-efficient. The current rate of U.S. efficiency averages around 35 percent, with new plants achieving up to 45 percent, depending on the type of design. The average OECD efficiency is 38 percent, but efficiency in China is only 28 percent. Increasing energy efficiency is a major action item for reducing carbon dioxide emissions because the greater the efficiency, the less coal that has to be burned to generate the same amount of electricity.

Coal gasification is a thermochemical reaction of coal, steam, and oxygen to produce a fuel gas largely made up of carbon monoxide and hydrogen. The integrated coal gasification combined cycle (IGCC) is more complicated than fluidized bed combustion, and in some ways is a step back into history. Manufactured gas, the predecessor of natural gas, was the reduction of coal to a mixture of hydrogen, carbon dioxide, carbon monoxide, and methane that was distributed by pipeline to consumers. Similarly, coal is not burned in coal gasification, but processed to produce combustible products.

The process begins with an air-separation plant that separates oxygen from nitrogen. Coal is milled and dried in preparation for being mixed with oxygen and hot water for gasification. Synthetic gases (syngas), mainly carbon monoxide and hydrogen, are then treated to remove solids (ash) and sulfur. Some of the nitrogen separated out by the air-separation plant is added to the clean syngas prior to burning to control nitrous oxide generation. The syngas is then burned in a combustion chamber to drive a gas turbine and, in turn, an electricity generator. In addition to burning syngas to drive a gas turbine, a steam turbine also runs off steam produced in the gasifier and in cooling the synthetic gas from the gasifier. The spent steam is partly reheated by the exhaust from the gas turbine and fed back into the steam turbine and partly condensed to water to feed the gasifier (the combined cycle part of the IGCC).

The byproducts of an IGCC plant can be hydrogen for the hydrogen economy or a range of motor vehicle fuels. The advantages of IGCC are increased energy efficiency of above 50 percent, less generation of solid waste, lower emissions of sulfur, nitrous oxides, and carbon dioxide, and recovery of chemically pure sulfur. In a conventional coal plant, carbon dioxide emissions are mixed with the intake air, which is 80 percent nitrogen. Carbon dioxide emissions from an IGCC plant are pure carbon dioxide that can be sold or captured. The government-subsidized Wabash River coal gasification plant, in operation since 1971, removes 97 percent of the sulfur, 82 percent of the nitrous oxides, and 50 percent of the mercury from plant emissions. The higher thermal efficiency of an IGCC plant reduces carbon dioxide emissions for the same amount of power output produced by conventional coal-fired plants that operate at a lesser degree of thermal efficiency. These plants cost considerably more than conventional plants and represent a higher level of technological sophistication, along with a greater technical challenge in operation.

Advanced hybrid systems that combine the best of both gasification and combustion technologies are under development. Here the coal is not fully gasified, but partially gasified to run a gas turbine with the residue of gasification also burned to run a steam turbine. Again, higher energy efficiencies with even lower emissions are possible. Ultra-low emissions technology is being funded by the ten-year, $1 billion FuturGen project to build the world's first integrated sequestration and hydrogen-production research power plant. FuturGen employs coal gasification technology integrated with combined cycle electricity generation. FuturGen will be the world's first zero-emissions fossil fuel plant capable of transforming coal to electricity, hydrogen, and carbon dioxide. Hydrogen can fuel pollution-free vehicles using low-cost and abundant coal as the raw material. Electricity can be sold as well as the carbon dioxide byproduct. FuturGen was killed by the Bush Administration in 2007 because of cost overruns, but it was reinstated in 2009 by the Obama Administration.[14]

As with everything else that has to do with this planet, nothing is constant. The concentration of carbon dioxide cycles over the ages peaked at 280 parts per million (ppm). Unfortunately, the start of the Industrial Revolution coincided with a cyclical peak. Since then humanity has added over 100 ppm from burning fossil fuels. The current carbon dioxide concentration of 385 ppm has never occurred before in the known climatic record of the world, which goes back about 400,000 years; thus, there is no precedent for judging its impact.

No practical way exists to capture the 3 tons of carbon dioxide emitted by driving a thirty-mile-per-gallon automobile 10,000 miles.[15] However, a stationary coal-fired power plant does lend itself to capturing and storing its carbon dioxide emissions. A typical large coal-burning power plant of 1,000 megawatts produces about 6 million tons per year of carbon dioxide, equivalent to the emissions of 2 million automobiles. There are about 1,000 of these plants in the world. Flue gas is roughly 15 percent carbon dioxide and the remainder mainly nitrogen and water vapor. Rather than passing the carbon dioxide through a smokestack for disposal in the atmosphere, flue gas passes through an absorption tower containing amines that absorb the carbon dioxide. An associated stripper tower heats the amines, releasing the carbon dioxide and regenerating the amines for another cycle through the absorption tower. The question is on what to do with the carbon dioxide from the stripper tower.

If the power plant sits on top of impermeable caprock below which is a horizontal porous sand formation filled with brine, carbon dioxide can be pumped down a vertical pipeline that reaches the porous formation and is then dispersed via horizontal pipelines running through the formation. The brine formation should be more than 800 meters beneath the surface, where the pressure is sufficient for the injected carbon dioxide to enter into a "super-critical" phase where its density is near that of the brine that it displaces. In addition to the carbon dioxide displacing brine, brine also absorbs some of the carbon dioxide. When carbon dioxide saturates an area of the formation, more horizontal pipelines are necessary to open up new areas. Huge volumes of carbon dioxide can be safely stored in this manner, but the geologic formation has to be about six times larger than a giant oil field to contain the sixty-year lifetime plant output of about 100,000 barrels per day of carbon dioxide condensed to a super-critical phase.

Carbon sequestering means that more coal has to be burned for a given level of power generation to dispose of the carbon dioxide, but it may be possible to also get rid of sulfur dioxide along with the carbon dioxide as a side benefit. The cost of carbon dioxide sequestering is equivalent to a $60 per ton surcharge on coal. This will work its way through the rate structure to the electricity consumer in the form of a rate hike of about two cents per kilowatt hour, or a 20 percent surcharge for consumers paying ten cents per kilowatt hour and more for those paying less. A problem with sequestering carbon dioxide is the relatively low percentage (15 percent) of carbon dioxide in flue gas. Presumably this would have to be separated, which is a very costly process. One idea being explored is burning coal with pure oxygen and then recycling the flue gas back through the combustion chamber to significantly raise the concentration of carbon dioxide in the flue gases for potential separation.

Carbon sequestration is not without its risks. Lake Nyos in Cameroon sits in a volcanic crater where carbon dioxide seeps into the bottom of the lake where it is held in place by the weight of the overlying water. One night in 1986, the lake overturned and released between 100,000 and 300,000 tons of carbon dioxide. Carbon dioxide, heavier than air, poured down two valleys, asphyxiating 1,700 individuals and thousands of livestock. Any geologic formation holding carbon dioxide must act as an effective lock against escape. Carbon dioxide can also be pumped into depleted oil and natural gas fields. Carbon dioxide associated with natural gas production in certain fields in the North Sea and Algeria is separated and sequestered in nearby porous geological formations.

A payback can be generated if carbon dioxide sequestering increases fossil fuel production. Carbon dioxide pumped into methane-rich fractured coal beds displaces the methane, which can then be gathered and sold. Carbon dioxide can also be pumped into older oil reservoirs, where its interaction with residual crude oil eases its migration through the porous reservoir rock to the production wells. One coal-burning plant pipelines its flue gas emissions over 200 miles for tertiary oil recovery.

Not all research is space age. One project is exploring the possibility of adding 10 percent biomass to existing coal-burning plants, which may reduce greenhouse-gas emissions by up to 10 percent. One Japanese utility adds 1 percent biomass in the form of solid municipal sludge to its coal intake, which has improved the performance of the utility.

There are two types of ash: fly ash removed by electrostatic or mechanical precipitation of dust-like particles in the flue gas and ash from the bottom of the combustion chamber. Ash represents a disposal problem; most ends up in landfills. Alternatively, ash from burning coal, gypsum from flue gas desulfurization units, and boiler slag can be made into "cinder" construction blocks, which consume less energy and release less pollution than cement construction blocks. Fly ash added to concrete makes it stronger, more durable, less permeable, and more resistant to chemical attack. Gypsum can be used as a low-grade fertilizer. These waste products can also be used as aggregate or binder in road construction. The Japan Fly Ash Association is dedicated to improving the quality of coal ash, establishing a reliable supply, conducting research for recycling coal ash as an environmental benefit. Research is also being conducted on methods to reduce metals emissions, particularly mercury.

ELIMINATING COAL NOT SO EASY

Carbon dioxide is the result of a chemical reaction that occurs during combustion. Switching from coal to oil or natural gas only reduces, not eliminates, carbon dioxide emissions. For the United States, further reliance on natural gas would be very costly if demand starts to exceed supply. Switching from coal to oil increases oil imports and U.S. dependence on Middle East oil exporters. Switching to nuclear and hydropower and renewables (wind, solar), and the hydrogen fuel economy would eliminate carbon dioxide emissions entirely, but major impediments have to be overcome. Switching from coal to nuclear power cannot occur unless public opposition to nuclear power is somehow lessened. Switching from coal to hydro is hampered by a lack of suitable sites for damming. Switching from coal to wind and solar, while possible as incremental sources of power, cannot replace coal because generation is dependent on the wind blowing and the sun shining. Switching from coal to hydrogen, while environmentally the best choice—along with solar and wind—is stymied by a less than fully developed and commercially feasible technology.

Much can be done to reduce coal-burning emissions without resorting to clean-coal technologies. Physical washing removes sulfur-iron compounds (pyretic sulfur) on the surface of raw coal, but not sulfur embedded in coal's molecular structure. While coal washing is prevalent in the United States, Europe, Japan, and other developed nations, it is not in China and India, whose high ash and sulfur content coal would benefit most from washing. Although China and India are making headway in washing coal, there are capital constraints in establishing washing facilities, and possibly a shortage of available water in certain areas. A shortage of capital might apply for India, but China, with a large balance-of-payment surplus, does not lack capital. In the past, China lacked the national will to deal with pollution because capital invested in pollution controls could not be dedicated to its economic development. Having said that, China is becoming more concerned over the environmental consequences of its economic policies and is starting to take remedial steps.

Closing small and inefficient mines can improve the environment. Fewer and larger mines ease inspection efforts by government authorities and larger coal volumes more easily justify investments to protect the health and safety of workers and minimize harm to the environment. Using coal and biomass in home cooking and heating is a major source of uncontrolled pollution in Asia. On the surface, greater amounts of coal would have to be burned to switch home cooking from coal to electricity, but burning coal in a few locations provides the means of monitoring and controlling pollution emissions.

The future of coal is certain: It already plays too significant a role in generating electricity to be dismissed out of hand. What is uncertain is what is going to be done to reduce its adverse environmental impact. Two projects may point the way in which the industry may evolve. The Prairie State Energy Campus (PSEC) is a $4 billion joint venture comprising eight public electric utilities and Peabody Coal, the world's largest coal company.[16] The venture is unique in that the participants own both the electricity-generating plant and the coal reserves set aside to service the plant. Coal will be from a mine located adjacent to the plant that will supply 6.4 million tons per year on a continuous basis using the room and pillar technique. The plant is the largest of its kind at 1,600 megawatts compared to the more typical large-sized plants of 1,000–1,200 megawatts and will be capable of serving around 2 million households when completed in 2012. The plant will burn pulverized coal ground to the consistency of talcum powder, which in conjunction with the supercritical steam generating technology, will have an efficiency advantage that will cut the

carbon footprint by 15 percent compared to existing plant technology. The plant will be among the cleanest coal-fueled plants in the nation. Coal will be burned at a lower temperature to reduce nitrous oxide emissions, which are further reduced by a selective catalyst-reduction unit that converts a portion of the nitrous oxide emissions to nitrogen and water. Dry and wet electrostatic precipitators will remove 99.9 percent of the particulates in the emissions, and an advanced sulfur dioxide scrubber using limestone and water will remove 98 percent of the sulfur. Mercury will be significantly reduced by the collective action of the selective catalyst reduction unit and the dry and wet electrostatic precipitators. Total emissions are expected to be cut in half compared to existing plants.

The other project is two proposed 629 megawatt IGCC plants to be built by American Electric Power, a major coal-burning utility. In a typical coal-burning utility plant, carbon dioxide is 15 percent of the flue gas whereas in an IGCC plant, the carbon dioxide is a separate gas stream, which allows carbon sequestration to avoid adding carbon dioxide to the atmosphere. American Electric Power is also involved with the technological development of using chilled ammonia that would isolate carbon dioxide from flue gas for sequestration in deep saline aquifers or for tertiary oil recovery. The company is also looking into the use of oxy-coal combustion (burning coal in pure oxygen) as a means of isolating a pure stream of carbon dioxide for sequestration or tertiary oil recovery.[17]

This is one side of the ledger. On the other side, hundreds of coal-burning utility plants are being built in China and India without regard for pollution control. These plants will add particulates and sulfur dioxide to the atmosphere that affect the health of those who breathe the fumes in addition to contributing to acid rain. China and India are trying to adopt clean technologies for generating electricity such as hydro and wind, but the magnitude of their growing demand for electricity is such that they are forced to rely heavily on coal. The problem is that this reliance on coal is on the basis of minimum concern over the environmental impact despite public announcements to the contrary.

To appreciate the magnitude of the problem, North America burns 18.4 percent of the world's coal with essentially no growth rate between 2000 and 2008. Europe including Russia burns 15.8 percent of the world's coal also with no net growth between 2000 and 2008. China alone burns 42.6 percent of the world's coal, greater than North American and Europe including Russia combined, and had a growth rate of 7.9 percent between 2006 and 2007. Adding in India, both nations burned 49.6 percent of the world's coal with growth of 9.2 percent between 2000 and 2008. These two nations represent half of the world's current consumption and are expected to maintain their robust growth rates. China alone is now the world's largest contributor to carbon dioxide emissions. Clearly, leaving these nations out of the successor instrument to the Kyoto Protocol is a major flaw.

NOTES

1. GlassOnLine Web site from www.glassonline.com/infoserv/history.html.
2. Barbara Freese, *Coal A Human History* (Cambridge, MA: Perseus Publishing, 2003).
3. Joseph S. Spoerl, "A Brief History of Iron and Steel Production," available from author at Saint Anselm College, Manchester, NH.
4. These statistics, as well as statistics on imports and exports and the role of coal in electricity generation, are available from the World Coal Institute at www.worldcoal.org/resources/coal-statistics/coal-steel-statistics/index.php.
5. I remember my father shoveling coal and having to remove and dispose of ashes from a coal furnace before converting to a heating oil furnace in a residential home on Long Island. I also remember my mother cooking on a combination wood- and coal-burning stove before switching to a propane-fueled stove in an upstate farmhouse. And I'm not that old!

6. John McQuaid, "Mining the Mountains," *Smithsonian Magazine* (January 2009), pp. 74–85.

7. The statistics in Table 4.1 are from *Sustainable Entrepreneurship* (December 2001), prepared by the World Coal Institute for the UN Environment Program; the figures are mostly for 2000, but a few are for 1999.

8. Volume data for all figures from *BP Energy Statistics* (London: British Petroleum, 2009). Sasol Corporation Web site www.sasol.com.

9. Clean Alternative Fuels: Fischer-Tropsch Fact Sheet published by the U.S. Environmental Protection Agency.

10. *World Energy Outlook* (Paris: International Energy Agency, 2008).

11. Sources in Figure 4.4 for the price of coal at FOB (free on board, used to specify that product is delivered and placed on board a carrier at a specified point free of charge at the mine mouth) is the U.S. Department of Energy www.eia.doe.gov/emeu/aer/coal.html, for bituminous coal in short tons. Source for the price of oil is *BP Energy Statistics* for $/bbl (dollar cost per barrel) FOB West Texas Intermediate; $/bbl price was multiplied by 7 in order to obtain $/metric ton (cost in dollars per metric ton). Natural gas prices in $/1000 cf were obtained from tonto.eia.doe.gov/dnav/ng/hist/n9190us3a.htm and translated to bbls at 5,610 cf/bbl. The price of coal was multiplied by 1.1 to convert from short tons to metric tons and then by 2 to convert physical tons to tons of oil equivalent to approximate the relationship between oil and coal in terms of equivalent energy released; these figures do not include shipping costs. Adjustments were made to price all three energy sources in 2008 dollars.

12. Kevin Krajick, "Fire in the Hole," *Smithsonian Magazine* (May 2005), p. 54ff.

13. World Coal Institute, London, Web site www.worldcoal.org for clean coal technology.

14. FuturGen is described in the U.S. Department of Fossil Energy Web site www.fe.doe.gov.

15. Robert H. Socolow, "Can We Bury Global Warming?" *Scientific American* (July 2005), p. 33ff.

16. Praire State Energy Campus Web site http://www.prairiestateenergycampus.com/.

17. American Electric Power Web site www.aep.com/citizenship/crreport/energy/generation.aspx.

5

THE STORY OF BIG OIL

When we think of oil, we think of gasoline and diesel fuel for motor vehicles, but the beginning of the oil industry was kerosene for illumination. Kerosene was the foundation of the Rockefeller fortune and marked the birth of Big Oil. Oil provided an alternative fuel for lighting; if oil ran out, it would be back to whale oil, tallow, and vegetable oils. Oil was not indispensable or vital to the running of the economy; now, no oil, no economy. The transition from a preferred fuel for lighting to something without which modern society cannot survive started with Henry Ford putting America on wheels in the early 1900s. The transition was complete by the First World War when military vehicles, tanks, and fighter aircraft fueled by oil played a pivotal role in securing victory for the Allies. Oil had become as important as armaments and ammunition in the conduct of war. During the Second World War, one of the principal targets of the Allies' bombing was the coal plants that produced gasoline to fuel the Wehrmacht. As a depleting resource, oil has moved beyond supporting war efforts to being a cause of war. This chapter looks at the historical development of two of the world's largest oil companies and the role that Big Oil may play in supplying the world with energy products as we proceed "Beyond Petroleum."

HISTORY OF LIGHTING

Prior to 1800, only torches, lamps, and candles lit the darkness of night. Torches were oil-, pitch-, or resin-impregnated sticks. Lamps—shallow rocks, seashells, or man-made pottery containing a natural fiber wick that burned grease or oil, animal fat, or rendered fat, called tallow—first appeared during the Stone Age. Candles go back to 3000 BCE and were made of tallow until paraffin wax, in use today, made its debut in the nineteenth century. To varying degrees, these modes of illumination produced more smoke than light.

In the early 1800s, the best lamp fuel was whale oil, which became increasingly expensive with the decimation of the whale population. There were plenty of alternatives to whale oil such as vegetable oils (castor, rapeseed, peanut), tallow, turpentine (from pine trees), and a variety of wood and grain alcohols. The most popular lamp fuel was a blend of alcohol and turpentine called camphene. Alcohol was obtained by distillation where vapors from a heated fermented mix of grain, vegetables, or fruits were separated, cooled, and condensed into a liquid. The distilling process for making alcohol for lamp fuel or whiskey was adopted in its entirety by the early oil refiners to separate the constituent parts of crude oil.

Another source of lighting in the 1700s and 1800s was coal gas. Gas emissions (hydrogen, carbon monoxide, carbon dioxide, and methane) produced by baking coal in a closed environment with insufficient air to support combustion were piped to street lamps in cities in Europe and America. Lamplighters lit the street lamps in the evening and extinguished them in the morning.

9

SUSTAINABLE ENERGY

This chapter discusses the meaning of sustainability and the principal sustainable energy sources: wind, solar, geothermal, and ocean (tidal, wave, and thermal). Their contribution to meeting world energy needs, along with their relative reliability compared to fossil fuels, will also be covered. Two sources of sustainable energy have already been dealt with: biomass in Chapter 3 and hydropower in Chapter 8. Some feel that nuclear power also qualifies as a sustainable energy source if reprocessing of spent fuel and breeding fuel can extend the life of uranium reserves for thousands of years.

THE MEANING OF SUSTAINABILITY

Sustainability is a modern-day concept, but it has deep roots as expressed by the following quote from Thomas Jefferson:

> Then I say the earth belongs to each. . . . generation during its course, fully and in its own right. The second generation receives it clear of the debts and encumbrances, the third of the second, and so on. For if the first could charge it with a debt, then the earth would belong to the dead and not to the living generation. Then, no generation can contract debts greater than may be paid during the course of its own existence. (1789)

Actually, this refers to financial sustainability where the debts of one generation should not encumber the next. It is a poignant countermark to the trillions of dollars that have been piled on the national debt along with assumed government guarantee obligations, not only in the United States but throughout the developed world, to keep the global financial system afloat and prevent national economies from crashing. But is it fair for one generation to mortgage the future of several generations for its benefit? And how can layering of more debt on top of a system awash with debt that cannot be repaid by debtors be a sustainable solution?

Theodore Roosevelt provided his version of sustainability:

> The "greatest good for the greatest number" applies to the [number of] people within the womb of time, compared to which those now alive form but an insignificant fraction. Our duty to the whole, including the unborn generations, bids us to restrain an unprincipled present-day minority from wasting the heritage of these unborn generations. (1916)

The present population, representing a small minority of the generations that are to follow, should not waste the heritage given them by their forebears. This was best exemplified by Theodore Roosevelt's setting aside wilderness areas as national parks preserving the heritage of his generation for future generations.

Susceptible to becoming a buzzword with no precise meaning, sustainability was given a universally accepted definition in the 1987 Report of the United Nations World Commission on Environment and Development as:

> meeting the needs of the present without compromising the ability of future generations to meet their own needs.[1]

The concept of sustainable development can be pictured as being supported by three independent pillars: social progress, economic growth, and environmental improvement. Another view of sustainable development is three overlapping circles: society, economy, and environment, signifying the strong interdependence among the three. The latter view better exemplifies the holistic approach of sustainable development to influence human progress. Sustainable development should not be a single-minded focus on an individual issue such as population control, nutrition, preservation of ecosystems, conservation of natural resources, urban livability, redistribution of wealth, energy usage, economic progress, industrial activity, and pollution control. However, all of these may be elements of a sustainability development program. A sustainable society is not impossible. The Indians of the Americas with a population of tens of millions, kept in check by tribal warfare and short lives, had a sustainable society before the Europeans arrived. Indian culture and religion were concerned with preserving the ecosystem. Hunting animals, gathering wood for shelter and burning for warmth and cooking, and raising crops did not reduce the animal and plant population or the fertility of the soil. The Indians showed the Pilgrims how to fertilize naturally by burying a fish with each kernel of corn and helped them in other ways that ensured their survival.

The Aztec and Inca cities of Mexico and Peru were certainly livable and had no surrounding garbage dumps (the Conquistadors considered them engineering marvels of unimaginable beauty before putting them to the torch). Sharing material possessions without a sense of legal ownership or property rights obviated the need for redistributing wealth. This paradise, however, did not include all Indian tribes. The Aztecs taxed neighboring tribes so heavily, in addition to using them as a ready source of victims for human sacrifice, that they eagerly sided with Cortez. Without these tens of thousands of willing allies, and the ravages of European-imported smallpox (an unintentional example of biowarfare), Cortez would not have been able to bring down the Aztec empire. Nevertheless, Native Indian civilizations were sustainable, which meant they could have gone on forever. Indians view modern civilization as a temporary structure, intrinsically opposed to nature and ultimately unsustainable. As a Mohawk Indian leader once said, "Not until the last tree has fallen, the last river has been poisoned, the last fish has been caught, will man realize that money isn't edible!"

Without becoming a modern industrialized society, this is what happened on Easter Island as discussed in Chapter 1. When first populated, the earth was fertile to grow crops, animal life was plenteous, and palm trees provided more than enough nuts for food and logs for making canoes to fish in the surrounding waters. Generations passed with the earth maintaining its fertility, animal life its population, and palms their numbers. But, alas, came a day when the demands of a growing population caused fertility of croplands to decline along with the population of animals and the number of palms. Life on Easter Island was no longer sustainable. An ever-increasing population hastened the inevitable demise of a society that had no way to escape.

Haiti is a nonindustrialized nation that has become unsustainable. The only difference between Haiti of today and Easter Island of centuries ago is that the people can escape. Unsustainability is a growing issue in other nonindustrialized nations in sub-Saharan Africa plagued by disease, economic deprivation, and the anarchy of failed states. The population in a number of these states is falling—a true sign of an unsustainable society. Some maintain that the sustainability of the entire planet is threatened by consumption of irreplaceable vital resources of which fossil fuels are but one, and also include loss of topsoil and falling water tables affecting agriculture, destruction of forests removing a vital carbon sink, and "strip-mining" the oceans obliterating marine life. Pollution of the environment, species extinction, and growing stress among peoples and nations do not bode well for the future. All this can be linked to an expanding world population unwisely pursuing ultimately unsustainable objectives; but this is beyond the scope of this book!

Perhaps a better way to look at sustainability in a more restricted fashion is to examine sustainability programs. One such program established by Monmouth University (New Jersey) is first a commitment to renewable energy. A 454 kilowatt solar photovoltaic system was installed on four campus buildings—the largest such installation at an educational institution "east of the Mississippi." The installation will pay for itself in eight years primarily by a 60 percent subsidy by the state on the installed cost and by fixing the cost of a portion of electricity usage in an environment of steadily rising rates. Its environmental benefit over its 25-year life is a reduction in carbon dioxide emissions equivalent to planting 1,500 acres of trees, or the emissions savings of not driving automobiles 13 million miles, or taking 1,000 automobiles off the road. There is also avoidance of sulfur and nitrous oxide emissions by not having to generate electricity with coal. Besides this commitment to renewable energy, the sustainability program also involves energy conservation and efficiency such as lowering water heater temperatures, adding reflective material on windows and roofs to reduce the air-conditioning load, replacing mechanical equipment with more efficient models, and installing energy-saving light bulbs. Water-resource reduction includes installing water-saving devices and intelligent scheduling and application of irrigating water for lawns, plants, and shrubs. Waste management involves recycling of glass, aluminium, paper, and electronic devices; the use of biodegradable disposable service ware and "trayless" service in the cafeteria; energy efficient hand dryers to avoid paper towel waste; purchase of fuel-efficient hybrid vehicles; and participation in various EPA environmental stewardship programs. Committees of staff, faculty, and students have been established to examine opportunities to reduce energy demand through conservation and efficiency measures, increase the use of renewable energy resources, provide outreach programs to educate campus and community stakeholders in energy and environmental sustainability policies and practices, take actions to reduce greenhouse gas emissions, and measure and verify sustainability actions in terms of their success in meeting goals and in lowering operating costs. The driver in Monmouth University's award-winning sustainability program is an ongoing effort to reduce its carbon and ecological footprints. The elements of Monmouth's sustainability program are fairly common among other institutional programs.

Companies may have sustainability programs. Manufacturing is conducted in a way that minimizes greenhouse gas and other harmful emissions. The productive output of machinery and equipment is maximized through an effective maintenance program to reduce downtime and intelligent production scheduling for full utilization. Less machinery and equipment have to be purchased for a given output when a plant operates at full utilization. Maximizing product quality means that the product will last longer between replacements, reducing demand for material resources and energy. The product itself should emit less in emissions when in operation (if applicable). This is perhaps best exemplified by General Electric's locomotives and aircraft engines that operate with fewer emissions to reduce their environmental impact. Both in manufacturing and in product operation, emission reduction is achieved by greater energy efficiency. Cutting emissions by using less energy also cuts manufacturing and operating costs. Thus sustainability programs actually improve profitability by maximizing manufacturing and operating productivity and in enhancing sales through a product's energy efficiency, quality, and longevity.

Corporations are also embracing reverse logistics as a part of sustainability programs. An example of reverse logistics is a major retailer that sent all returns to a dumpsite. A company specializing in reverse logistics took over the handling of returns. Returned items were either sent back to the manufacturer for credit, repaired, or working components removed for resale to create value as a substitute for a loss. Using repaired items and salvaged components for resale also reduces the number that have to be manufactured. Companies that rebuild heavy construction equipment and diesel engines and recycle computers and other electronic products contribute to sustainability by cutting emissions associated with manufacturing new equipment and products. Corporate sustainability programs aimed at reducing their carbon and ecological footprints improve profitability just as institutional sustainability programs cut costs.

Housing two-thirds of the world's population, cities and towns are an important part of global sustainability. Increased urbanization will cause their share of global carbon emissions to grow from 70 percent in 2008 to 76 percent by 2030. Urban sustainability is focused on livability and on the reduction of a city's carbon and ecological footprints. The role model for urban sustainability is Europe, where cities tend to be more compact with much less urban sprawl than American cities. European cities generally rely more on public transport, bicycles, and walking rather than automobiles. They have greater control over land use and have a higher priority to improving the environment than cities elsewhere. Housing is diverse design-wise, not overly concentrated as in the monolithic high-rise rabbit-coop structures that plague many cities. Shopping areas, parks, and small city farms are interspersed in residential areas along with places of employment. Tree-lined roads are set aside for pedestrians and bicycles, and public transport systems rely more on trams than buses, essentially eliminating the need for automobiles. Historic sites are preserved rather than being bulldozed for high-density buildings.

Construction codes promote "green" urbanism by being less demanding on the environment in terms of consuming energy and generating waste along with encouraging architecturally attractive designs. Buildings with flat roofs may have either topsoil with gardens that act as insulation or solar panels for electricity or both. Zero-energy building designs, on balance, consume no energy by means of greater insulation, energy-efficient lighting and appliances, and solar water heating to reduce energy demand combined with solar panels and/or wind turbines for electricity generation. Zero energy means that the sales and purchases of electricity from and to a utility are about equal; that is, no net purchases of electricity. Industrial enterprises are designed to fit unobtrusively within city environs close to residential areas to allow employees to walk or bicycle or take a tram to work. The objective of urban sustainability development is for a city to become a self-contained unit, providing the economic means and the ecologically-desirable surroundings that allow residents to work and live within city limits on workdays and to rest and pursue leisurely activities on weekends. Urban sustainability is not a national or state program but a local program voluntarily undertaken by individual cities to improve their livability.[2]

Though European cities have been in the vanguard, they are not alone in reducing their ecological footprints as part of more encompassing sustainability programs. In 2005, the mayor of Seattle spearheaded the formation of the U.S. Conference of Mayors Climate Protection Agreement where cities pledge to reduce local greenhouse gas emissions to 7 percent below 1990 levels by 2012 as part of a wider program of urban sustainability. By 2008, 850 mayors representing 80 million Americans had signed the Agreement. In 2007, the mayor of New York City hosted the second C40 Large Cities for Climate Protection conference involving the world's forty largest cities and also spoke at the Bali Climate Change Conference on the role that cities can play in mitigating the effects of global climate change. Examples of city networks established for pursing sustainability goals are the Nottingham Declaration Partnership (U.K.), Partners for Climate Protection (Canada), Network of Cities for Climate (Spain), Kyoto Club (Italy), and Coalition of Local Governments for Environment Initiative (Japan). Individual cities have announced climate-change policy targets within more encompassing sustainability programs such as Toronto's 80 percent reduction of emissions from 1990 levels by 2050, London's 60 percent reduction from 1990 levels by 2025, Bristol (U.K.) 60 percent reduction from 2000 levels by 2050, Berkeley (U.S.) 33 percent reduction from 2000 levels by 2020, Tokyo's 25 percent reduction from 2000 levels by 2020, and Paris' 25 percent reduction from 2004 levels by 2020. San Jose (U.S.) plans to have all its electrical power from renewable energy sources within fifteen years and intends to take advantage of this demand to create new jobs in solar energy and make San Jose a center for companies pursuing clean technologies.

China's percentage of urbanization will increase from 40 percent to 60 percent by 2030. Its 11th Five-Year Plan calls for a 20 percent energy-intensity reduction by 2010. This effort is spearheaded at the national and provincial level, not at the city level, reflecting China's preference for centralized authority. With intense competition among cities to attract investment, city governments are taking the initiative to address concerns about energy security and local air pollution by limiting the role of coal, promoting industrial structural change from primary to less-polluting, more energy efficient, secondary industries, and improving public transport. Some Chinese cities are trying to develop low-carbon environments and new cities such as Dontang Eco-City, near Shanghai, are being built with an emphasis on clean energy and a clean environment as part of sustainability programs. A local air pollution control policy was effective in preparing for the 2008 Beijing Olympics. Following Beijing's example, Shanghai established emission-control measures to improve its air quality by prohibiting highly polluting motorcycles on its main thoroughfares, restricting the number of vehicle licenses, and taking action to develop public transport to enhance its future sustainability as a major world city.[3]

Sustainable development is not limited to reducing the ecological footprint of institutions, companies, and population centers in the developed world. In some respects, sustainable development will increase mankind's ecological footprint by its concern for the have-nots of the world: the 1.3 billion people without access to clean water, the 2 billion people without access to electricity, the 3 billion people (half of humanity) without access to adequate sanitation and who earn less than $2 per day. Sustainable development is also concerned with the inequality of wealth distribution where the top 20 percent of the world's population account for 86 percent of consumption, and the bottom 20 percent account for only 1.3 percent.[4]

Sometimes, improving the living standards of the world's poor as part of a sustainability development program can have undesirable consequences. Some years ago, women in India had to manually haul drinking and cooking water from wells until rural electrification allowed small electric water pumps to be installed that eased their plight. Then it was discovered that the water could also be used for irrigation to improve agricultural crop yields, but this required installing large water pumps. Reducing the manual workload for women and improving agricultural output are admirable goals in terms of sustainability development. But irrigation expanded to the point of being the largest consumer of electricity in the agricultural sector, which of itself accounts for nearly half of India's electricity consumption, much of which is powered by burning coal.[5] Along with the unfortunate consequence of added carbon emissions is a falling water table measured in hundreds of feet—a harbinger to a water crisis with a food crisis in its shadow.

Concerns about encouraging a sustainable society were first voiced at the 1992 Rio Earth Summit attended by 152 world leaders, but no real action plan to pursue sustainability was initiated in its aftermath. The follow-on 2,500-page 2005 Millennium Ecosystem Assessment concluded that the world faces a bleak future in meeting the goals of sustainability by various measures including the growing inability of nature to purify the amount of air and water polluted by mankind, the massive wave of species extinctions, and the general lack of progress in moving towards a sustainable world.

Focusing on the concept of sustainability with regard to energy, a sustainable source of energy should be renewable and environmentally benign. Though not environmentally benign, some consider nuclear power with reprocessing as a sustainable energy source. To be fair, no renewable energy source is entirely environmentally benign—even wind has its opponents who are concerned with bird kills, wind turbine noise, and the despoiling of the natural landscape. While sustainable energy sources may seem inexhaustible, there are capacity limits in terms of the number of wind turbines and solar panels just as there are capacity limits in the number of coal-fired generation plants. Growth in capacity is limited by capital, manufacturing and construction constraints, and an equally important constraint in the form of the willingness of society to build more capacity.

Biomass is a sustainable source of energy as long as a crop is grown, burned for its energy content, and replaced by another. Under these conditions, there is no net addition of carbon dioxide to the atmosphere because the carbon dioxide released from burning is absorbed in growing the replacement crop. But as noted in Chapter 3, ethanol from corn in the United States consumes about as much fossil fuel as the amount of ethanol produced and provides, at best, marginal reduction in carbon emissions while ethanol from sugar in Brazil effectively reduces fossil-fuel demand. Biomass is limited by the availability of arable land for raw materials. Deforestation for food and nonfood crops adds carbon dioxide to the atmosphere as more biomass is burned than is replenished and is not sustainable; at some point, the forests are gone. Biofuel crops that displace tropical forests have less capacity to absorb carbon dioxide even after taking into account the savings in biofuel carbon emissions. Since biomass, nuclear, and hydro as renewable energy sources have been covered in previous chapters this chapter concerns itself with alternative and renewable energy sources of wind, sun, heat within the earth (geothermal), and the movement of water (tides, currents, and waves).

A major difference between conventional and renewable sources of energy (other than geothermal) is reliability. Electricity can be generated at the dispatcher's whim up to a plant's rated capacity for a generator fueled by fossil and biomass fuels, nuclear power, and geothermal energy. This is not true for other sources. Hydropower depends on rainfall, which affects the water level behind a dam. Wind and solar power depend on whether the wind is blowing or the sun is shining. Though tidal energy is predictable, there is no guarantee that peaks in electricity generation coincide with peaks in electricity demand. Wind, solar, tidal, and wave sources can certainly be tied into an electricity distribution grid and contribute to the electricity pool "weather permitting," but they can only displace, not replace, conventional sources of energy unless backup sources of standby power are available to guarantee their reliability.

WIND ENERGY

Wind results from differences in air temperature, density, and pressure from the uneven solar heating of the earth's surface. Like ocean currents, wind currents act as giant heat exchangers, cooling the tropics and warming the poles. Successful placement of wind turbines are in areas with persistent winds such as where geological formations force wind to flow through relatively narrow mountain passages as in California or along the east side of the Rockies, making the northern plain states ideal for wind turbines. Another area of desirable wind patterns are along coastlines where, during the day, air above land heats up more quickly than air over water causing a sea breeze of heavier, cooler air over water rushing in to take the place of rising warmer air over land. At night, a land breeze results from air cooling more rapidly over land than over water. Coastlines and offshore waters are high on the list for wind-development projects to take advantage of their fairly reliable wind patterns.

Historical Development

The history of wind as an energy source goes back to the dawn of history. Around 5000 BCE, the ancient Egyptians employed boats fitted with sails to move goods up and down the Nile River. The Phoenicians later adapted the sail for a more vigorous marine activity of trading between Mediterranean ports. Despite the apparent advantage of sail as a means of moving goods, it took millennia for wind power to replace those who performed what must have been the most tiring and tedious of jobs: that of oarsmen. Eventually, sail became the ubiquitous means of transport throughout the world until the appearance of coal-fired merchant ships in the nineteenth century. Their chief advantage over sail was being capable of keeping to a schedule. The Clipper ships were a dying technology's response to progress with the thought that speed would be a competitive edge over slower moving coal-fired vessels. But alas, speed was contingent on the wind blowing in the right direction. The 1869 opening of the Suez Canal was the death knell to Clipper ships on the Pacific tea trade as now slower, but steady-speed coal-fired merchant ships had a much shorter route to ply between Europe and Asia (sailing vessels had a difficult time navigating the narrow Suez Canal and had to pass around Cape of Good Hope to reach the Pacific). The era of the Clipper ship lasted only a few decades. Interestingly, the subject of sail-assisted merchant vessels has been revived in recent years whenever the cost for bunkers (ship's fuel), reflecting spikes in oil prices, consume half or more of voyage revenue. Sail is still used in the Middle East, Africa, and Asia for commercial fishing and local trade.

The first land-based windmills were developed in Persia and the Middle East around 500–900 CE (although there is a claim that China used wind power to pump water as early as 200 BCE).[6] These early windmills employed woven reed or wooden sails, adapted from sailing vessels, to either grind grain or pump water. Grinding grain requires a horizontal grinding stone that must be driven by a vertical axis. Early windmills with sails powered vertical shafts of reed bundles or wood. (Sail-powered vertical axis windmills can be found today in Crete pumping water for crops and livestock.) Returning merchants and crusaders from the Middle East and Persia brought the idea of the windmill to Western Europe. This evolved from a vertical-axis design to the more efficient horizontal-axis configuration for capturing wind energy, but this also required gearing to translate the motion of a horizontal axis to a vertical axis to drive a grindstone. The earliest illustration of these windmills, dating back to 1270, shows a four-bladed mill mounted on a central post or post mill with wooden cog-and-ring gears to translate the motion of the horizontal shaft to a vertical shaft to turn a grindstone. In 1390, the Dutch refined the design of the windmill with a horizontal post mill at the top of a multistory tower, which was translated to a vertical post mill that passed through separate floors for grinding and removing chaff and storing grain, with the bottom floor serving as living quarters for the wind-smith and his family. This refined windmill was also adapted for draining lakes and marshes in the Rhine River Delta to expand agricultural land, and later, with the building of dikes, to create a nation by taking land away from the sea. Holland had 8,000 windmills in 1650, England 10,000 windmills in the early 1800s, and Germany more than 18,000 windmills in the late 1800s.[7]

The process of perfecting the windmill sail and in making incremental improvements in efficiency and reliability took about 500 years. By the time the process was complete, windmill sails had all the essential features incorporated by designers of modern wind turbine blades. Windmills in Europe were eventually replaced with the convenience and reliability of coal-fired steam engines.

In the United States, windmills for pumping water were perfected during the nineteenth century beginning with the Halladay windmill in 1854 and continuing on with the Aermotor and Dempster designs still in use today. The original mills had thin wooden slats nailed to wooden rims with tails to orient them into the wind. An important refinement of the American fan-type windmill was the development of steel blades in 1870, which allowed for a more efficient and lighter design. Between 1850 and 1970, over six million small (1 horsepower or less) mechanical output wind machines were pumping water for livestock and home use.[8] Large windmills with blades up to 18 meters (59 feet) in rotor diameter (the circle swept by the tip of the blades) supplied the large water requirements of steam locomotives where water had to be pumped from below ground.

The wind turbine is the opposite of a fan. A fan consumes electricity to power a motor that turns a rotor with attached blades to move air. In a wind turbine, moving air turns the blades attached to a rotor that drives a generator. The first windmill to generate electricity was built in Cleveland, Ohio, in 1888 by Charles F. Brush. The Brush wind turbine had a post mill with a multiple-bladed rotor 17 meters (56 feet) in diameter and a large tail hinged to orient the rotor properly to the wind. A step-up gearbox turned a direct current generator at its required operational speed. This design did not work well and in 1891, the Danish entrepreneur, Poul La Cour, improved the design and developed the first electricity-generating wind turbine of 25 kilowatt (kw) output with four-bladed airfoil shaped rotors. The higher speed of the La Cour rotor made these machines practical for electricity generation. By the end of the First World War, cheaper and larger fossil-fuel steam plants started to replace the electricity-generating wind turbines that dotted the Danish landscape. By the mid-1920s, small electricity-generating wind machines (1–3 kw), developed by Parris-Dunn and Jacobs Wind-Electric, were popular in the Midwest and Great Plains to provide lighting for farms and charge batteries for powering crystal radio sets. Electricity from these wind turbines soon began to power an array of direct current motor-driven appliances including refrigerators, freezers, washing machines, and power tools. However, their sporadic operation when the wind ceased blowing was a problem. In the 1930s, the Great Depression spurred the federal government to sponsor the Rural Electrification Administration's program to stimulate depressed rural economies by extending the electricity grid throughout rural America, ending the days of wind-generated electricity. (History likes to repeat itself, but with a twist. One of the Obama administration's programs to stimulate the economy is the extension of transmission lines to isolated areas with persistent winds to promote wind-generated electricity or to areas with lots of sunlight to generate solar electricity.)

The development of bulk-power, utility-scale wind energy conversion systems was first undertaken in Russia in 1931 with the 100 kw Balaclava wind generator. This wind turbine operated for about two years on the shore of the Caspian Sea. Subsequent experimental efforts in the United States, Denmark, France, Germany, and Great Britain between 1935 and 1970 demonstrated that large-scale wind turbines worked, but they failed to produce a large practical electric wind turbine. In 1945, the largest wind turbine was the Smith-Putnam machine installed on a Vermont hilltop called Grandpa's Knob. This horizontal-axis design featured two-blades with 175-foot rotor diameter and generated 1.25 megawatts (MW) in winds of about 30 mph. Its power was fed to the local utility network, but after only several hundred hours of intermittent operation one of the blades broke off near the hub from metal fatigue, ending its life.

European developments continued after the Second World War when temporary shortages of fossil fuels led to higher energy costs. In Germany, Professor Ulrich Hutter developed a series of advanced, horizontal-axis designs of intermediate sizes that utilized modern, airfoil-type fiberglass and plastic blades with variable pitch to provide lightweight and efficient generation of electricity. This design sought to reduce bearing and structural failures by "shedding" aerodynamic loads rather than "withstanding" them. Hutter's advanced designs achieved over 4,000 hours of operation before the experiments were ended in 1968. In France, G.J.M. Darrieus began the development of vertical-axis rotors in the 1920s comprised of slender, curved, airfoil-section blades attached at the top and bottom of a rotating vertical tube resembling an eggbeater. The research ceased until two Canadian researchers took on major development work in the late 1960s.

Government Involvement in Developing Wind Turbines

The popularity of using the energy in the wind has always fluctuated with the price of fossil fuels. Interest in wind turbines waned when fuel prices fell after the Second World War, but revived when oil prices skyrocketed in the 1970s. The U.S. federal government's involvement in wind energy research and development (R&D) began in earnest within two years after the 1973 oil crisis to refine old ideas and introduce new ways of converting wind energy into useful power. Many of these approaches were demonstrated in wind farms, a grouping of wind turbines located in a single area that fed electricity into a utility grid. Despite the speed with which it was initiated and the early show of promising results, this program ultimately proved to be ineffective with the withdrawal of government funding before final success could be achieved.

Nevertheless, other federal R&D activities such as at Sandia National Laboratories resulted in the design, fabrication, and testing of thirteen different small wind-turbine designs (ranging from 1–40 kw), five large (100 kw–3,200 kw or 3.2 MW) horizontal-axis turbine (HAWT) designs, and several vertical axis (VAWT) designs ranging from 5 to over 500 kw. Most of the funding was devoted to the development of multimegawatt turbines in the belief that U.S. utilities would not consider wind power to be a serious power source unless large, megawatt "utility-scale" turbines were available. Wind turbine development in the United States progressed from blade lengths of 5 to 10 to 17 meters (16 to 33 to 56 feet). The latter machine, commercialized by FloWind, used much of the technology developed by Sandia National Laboratories, but a real market for this technology never emerged.

While Canadian development was focused on a 4 megawatt (MW) Project Eole turbine on Magdalen Island in the St. Lawrence River, the National Aeronautics and Space Administration (NASA) Plum Brook Ohio facility became involved with wind turbines and started development of the 100 kw MOD-0 in 1975, and rapidly moved through several generations including the MOD-1 and the 100-meter (328-foot) diameter MOD-2 wind turbines. The program was plagued by not realizing the importance of "teetering" hubs essential for reducing dynamic loads in two-bladed machines created by the tower shadow. After initial failures, the first "real" NASA wind turbine was the MOD-2. Three of these machines operated for several years providing valuable engineering data to pinpoint and correct several design weaknesses. Unfortunately, these pitfalls were all that were needed to provide detractors with enough ammunition to end the program in 1981. Nevertheless, lessons learned on the MOD-2's were incorporated in the huge 3.2 MW MOD-5B wind turbine at the Makani Moa'e wind farm in Kahuku, Oahu, operated by Makani Uwila Power Corporation. The wind turbine had two blades with a rotor diameter of 320 feet and was the largest-sized wind turbine in the world until a few years ago when 3.6 MW turbines became commercially available. Wind turbines are getting larger in capacity to take advantage of economies of scale with the next generation of 5 megawatt turbines already in their testing phase.

Another federal effort started in 1976 was to develop a reliable wind turbine to perform as envisioned in a federal wind-application study. Within four years, thirteen wind-turbine designs were developed for five size-range categories including 1–2 kw High Reliability, 4 kw Small Residential, 8 and 15 kw Residential and Commercial, and 40 kw Business and Agricultural. This development work led to the 1–3 kw and 6 kw small wind turbines commercialized by Northern Power Systems and still being sold for remote power users and a three-bladed 40–60 kw wind turbine installed by the hundreds in California wind farms by Enertech. Wind farms in California were the vanguard in commercializing wind energy and were the result of both R&D efforts undertaken by the federal government and financial incentives established by the Public Utility Regulatory Policies Act (PURPA) of 1978. This Act required state regulatory commissions to establish procedures for nonutility companies to sell electricity to utilities generated from renewable energy sources, waste, and cogenerating plants run on natural gas. California state regulators, fearing that oil-fueled electricity-generating plants would be vulnerable to falling oil production in California and Alaska, were particularly aggressive in carrying out PURPA provisions. They required California utilities to buy electricity generated from wind farms at a premium over conventional sources to induce the development of wind energy. As a result, California would eventually become the home of over 17,000 wind turbines, which produce individually between 50–600 kw of electricity. For a measure of scale, a single wind turbine producing 600 kilowatts or 600,000 watts can generate enough electricity for 6,000 100-watt light bulbs. Major California wind farms are located at the mountain passes that experience persistent winds much of the time such as the Altamont Pass east of San Francisco, Gorgonio Pass near Palm Springs, and at Tehachapi south of Bakersfield. Wind farms in California made up most of U.S. wind turbine installations until the early 1990s. At the height of their power potential, these turbines had a collective rating of over 1,700 megawatts (1.7 gigawatts), sufficient in the United States to supply a city of 1 million people—but only when the wind was blowing at all their various locations. Fortunately, periods of high winds over the coastal hills correlated fairly well with timing of high commercial and residential air-conditioning loads in the summer. The key subsidies making wind-turbine investments financially attractive were a 15 percent federal energy credit, a 10 percent federal investment credit, a 50 percent California state energy credit, and a high electricity rate mandated by state regulators that had to be paid by utilities for electricity produced from alternative sources. The high rates paid for electricity produced by wind farms and the subsidy benefits provided by the federal and state governments were neatly packaged into investment products by private financial firms to garner the necessary capital from individuals and companies to build California's wind farms.

The beneficiaries of the heavy federal wind-energy funding programs were supposed to be the large U.S. aerospace and construction firms developing the MOD-2, MOD-5, and the intermediate sized MOD-6 wind turbines. But an increase in military expenditures reduced the interest of aerospace firms in risky new business challenges like wind turbines. The "counter-culture" wind-energy entrepreneurs at Rocky Flats, Colorado, founders of the American Wind Energy Association in the mid-1970s, became the driving force in the development of wind turbines. Unfortunately, a combination of design problems, the Reagan administration's attitude toward deregulation, and a period of low oil prices removed the incentives to pursue renewable energy sources and the wind energy business slowed considerably in the 1980s.

Nevertheless, there was still activity. In contrast to American companies that pursued two-bladed wind turbines, Danish firms developed three-bladed wind turbines based on the Gedser mill design. The design, considered somewhat primitive and inefficient, but well understood, was modernized with fiberglass blades. By 1986, the Danes captured 50 percent of the U.S. wind farm market replacing hundreds of inoperable U.S. turbines cluttering the California landscape. Design shortcomings became apparent when high California wind loads began to pulverize the poorly manufactured Danish blade roots, requiring an expensive "fix" for thousands of turbines. Even though wind farm operators were weighed down with high maintenance costs and constant repairs to keep their wind turbines running, the U.S. wind farm demand for new intermediate-size wind turbines was still alive. Then the wind farm operators were hit with the end of the federal energy credits in 1984 and the phase-out of California state credits shortly thereafter. Fortunately for the wind farm operators, California utilities were required to maintain artificially high buyback rates for the output of wind turbines into the 1990s, when many of the wind turbines had long since been paid off, thus making investments in wind turbines quite profitable. Although sales of small wind turbines during this period were slow, the volume was sufficient to provide business for several manufacturers of wind turbines designed for water pumping and electricity generation at remote locations such as Southwest Wind Power and Bergey Windpower. In general, however, the U.S. market lagged and gradually declined during the 1980s and into the 1990s.

From Tiny Acorns to Mighty Oaks

During this period, wind-turbine installations increased steadily in northern Europe. Denmark was the leader, drawing on its earlier role in wind energy. The higher cost of electricity and excellent wind resources in northern Europe created a small but stable market for single and cooperative-owned wind turbines. Driven by high utility power rates for wind power, the installation of 50 kw turbines rapidly gave way to 100 kw, then 200 kw, then 500 kw, and now 1.5 megawatt wind turbines by cooperatives and private landowners in the Netherlands, Denmark, and Germany. The installation of over 70,000 megawatts (70 gigawatts) of European wind capacity by 2009 supports a thriving private wind-turbine development and manufacturing industry.

In the 1990s, robust wind-development activity in Europe contrasted with the U.S. penchant for low utility rates based on cheap coal and natural gas, which when coupled with deregulation of the utility industry, virtually strangled wind energy development. In the 1990s, the California wind farm market was further pummeled by the expiration or forced renegotiation of once attractive power purchase contracts with the major California utilities—Southern California Edison and Pacific Gas and Electric. Despite this negative outlook, in 1999, "green power" initiatives in Colorado, Texas, and elsewhere spurred U.S. wind-energy development. New wind farms included a cluster of Zond Z-40 turbines operated for a southwest Texas utility, a wind farm of 46 Vestas machines at Big Spring, Texas, a 10 megawatt wind farm in northern Colorado with other turbines in the upper Midwest, plus "repowering" of California projects with larger and more modern units. Entrepreneur Jim Dehlsen founded the company that manufactured Zond turbines, now part of GE Wind. Vestas is the leading Danish wind-turbine manufacturer with a 20 percent global share of the wind-turbine market. Other major manufacturers are Gamesa and Acciona (Spain); Suzlon (India); Enercon, Siemens, and Nordex (Germany); and Goldwind and Sinovel (China).[9] Foreign wind-turbines manufacturers have set up factories in the U.S. to handle the resurgence in wind energy.

Perhaps the greatest incentive for the revival of wind energy was the fall in the price of electricity from wind turbines from $1.00 per kilowatt-hour in 1978 to under $0.05 in 1998, and $0.025 when new large wind turbines came online in the early 2000s. However, it is difficult to accurately compare the costs of wind farms and fossil-fuel plants because their respective cost drivers are so vastly different. Low installed-cost-per-kilowatt figures for wind turbines are misleading because the cost estimates are based on full-capacity operation. But wind is not reliable, and actual load factors vary between 25 and 40 percent of capacity compared to average load factors for fossil-fuel power plants of 50 to 70 percent of capacity with the ability to ramp up to 100 percent capacity at will, an option that wind turbines cannot replicate. Widely dispersing wind farms and placing them in areas where acceptable wind conditions are prevalent much of the time increase the reliability of wind power. Moreover, the cost estimates of wind-energy projects frequently neglect the need for backup sources of power in case the wind stops blowing and the need to construct transmission lines from generally remote areas amenable for generating wind energy to the electric power grid.

While fuel is free, wind turbines have operating costs such as insurance and maintenance. Film clips of wind farms always show a number of idle wind turbines, which gives an inkling of reliability. With the top of wind turbines a few hundred feet in the air, some method has to be devised to get repairmen up to where the electricity-generating equipment is located. On land, large cranes are necessary to hold ladders in place for the workmen to climb. In offshore waters, helicopters have to be employed to lower repairmen to the dome-shaped top of wind turbines. Repair costs have to reflect the use of large cranes or helicopters and the inherent danger of climbing hundreds of feet up a ladder in gusty winds or being lowered on a dome shape in windy conditions compounded by the helicopter's downdraft prior to fastening oneself to a safety line.

Like water flowing in a river, the amount of generated electricity is determined by the energy contained in the wind passing through the area swept by the wind turbine blades known as the wind-power density. Wind-power density depends on the cube of the wind speed (when wind speed doubles, the wind-power density goes up by a factor of eight) and also on air density and temperature (lower altitudes and cooler temperatures increase wind-power density). A turbine has four output phases depending on wind speed. No power is generated when wind is below a minimum speed. Above the minimum speed, electricity output rises rapidly with increasing wind speed until the wind speed attains a threshold level. Above this, electricity output is constant at the turbine's rated capacity even with increasing wind speed to avoid overstressing the wind turbine. Turbine blades are designed to rotate with a frequency that ensures optimum efficiency and maximum yield of wind-power density that can be converted to electricity with minimum tower oscillation, but are also designed to become less efficient at wind speeds that can damage the tower supporting the turbine or the blades themselves. When wind speed is too high, the wind turbine stops producing electricity and assumes a mode of operation that protects the blades and tower against physical damage. Large commercial wind turbines operate between 10 and 20 revolutions per minute (rpm) where the rate of rotation depends on the wind speed. The variable rate of rotation generates a variable-frequency electrical current, which is converted to direct current (DC). Electricity can be transmitted for long distances in the traditional manner as high voltage AC, but recent technological progress now allows high-voltage DC transmission. Either at the start or less frequently at the end of its transmission to an electricity grid, direct current is converted to a fixed frequency alternating current as required by the utility (e.g., 60 cycles per second in the U.S. or 50 cycles per second in Europe).

Electricity from wind is experiencing explosive growth. From the tiny acorns planted in the 1980s in California, mighty oaks are growing. Global wind-energy capacity totaled 120 gigawatts in 2008, representing a compound growth rate of 27 percent since 2000 when total output was 17.4 GW shown in Figure 9.1.[10]

Figure 9.2 shows 2008 installed wind-power capacity and planned capacity additions. The United States, which was in third place in 2003, is now in first slightly ahead of second place Germany. Future additions to U.S. wind-energy capacity have four major supports. One, the Obama administration is expected to establish a national renewable electricity standard (RES) of 25 percent by 2025, with a near-term standard of 10 percent by 2012. Although the RES applies to all forms of renewables (biofuel, wind, solar, geothermal, hydro and others), wind will be a prominent player

Figure 9.1 **Global Wind Power Installed Capacity** (GW)

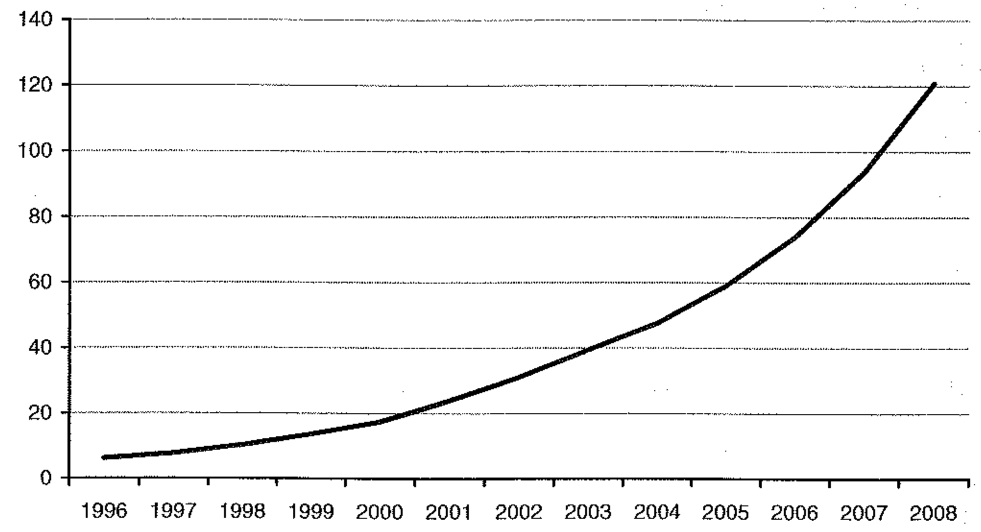
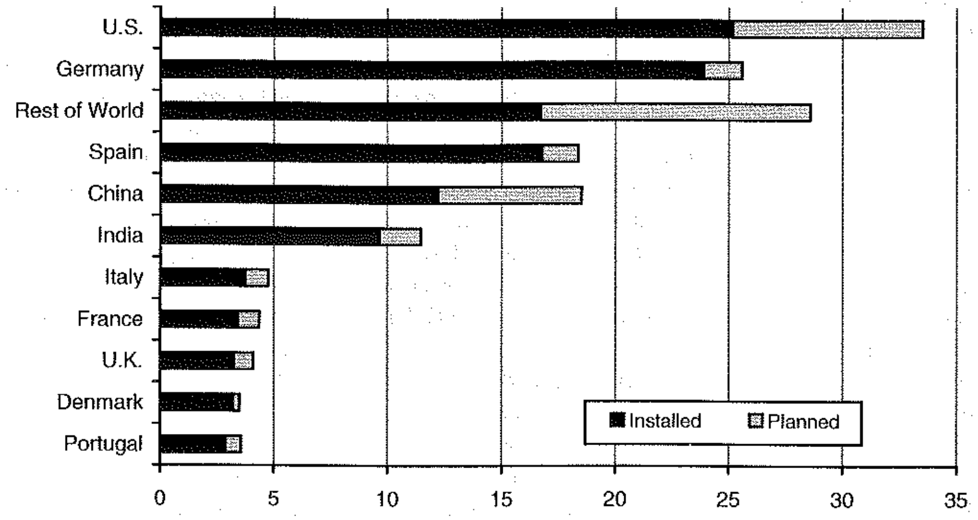


Figure 9.2 **Installed Capacity as of 2008 and Planned Capacity** (GW)



as its cost is more closely aligned to conventional forms of electricity. Two, the Obama administration is expected to support a high-voltage interstate transmission "superhighway" to tap the nation's vast renewable energy sources. Three, some form of cap and trade program is expected to be established with regard to carbon emissions for climate control. This will make fossil fuels more expensive and provide an additional economic incentive for investments in renewables.

Four, the American Recovery and Reinvestment Act of 2009, signed into law by President Obama in February 2009, is intended to jumpstart the economy by taking measures to modernize U.S. infrastructure, enhance energy independence, expand educational opportunities, preserve and improve affordable health care, provide tax relief, and protect those in greatest need. With regard to energy, the Act provides a 30 percent grant of the installed cost of renewable energy projects with a termination date for approving such projects of January 1, 2013. The grant replaces a 30 percent tax credit, which requires a firm to be profitable for the tax credit to be of value. The 30 percent grant is independent of a company's profit—it is a free gift to help fund a project that never has to be repaid. Moreover the grant is effective for four years, quite unlike past tax credits that turned "on and off" with frequent regularity, causing investors to shy away from investing in renewable energy sources.

The leading state from the point of view of both installed and planned additions is Texas, followed by Iowa at less than half that of Texas, with California in third place with very little in the way of capacity additions. Despite the allure to build wind farms, T. Boone Pickens, an oil man with his own solution to the oil problem, abandoned what would have been the world's largest wind farm (4 gigawatts) in the Texas Panhandle in 2009 citing doubts over the actual construction of a long-distance transmission system that would be necessary to connect the wind farm with the electricity grid, problems in obtaining financial support, and low natural gas prices. Wind farms supply electricity to meet variable demand, which is generally priced at the cost of electricity generated by natural gas during the day and coal and nuclear at night. A falloff in natural gas prices lowers daytime electricity rates, which cuts the revenue stream for wind farms. Pickens is still involved with other wind projects, but this particular project is now on hold until the global financial situation stabilizes along with some real progress in the government's intention of extending the transmission system to service wind farms.

Another favored area for wind farms is the offshore waters of New Jersey and Delaware. If there were wind farms about fifteen miles offshore along much of the coastline, electricity generation would make Delaware and New Jersey not only self-sufficient, but leading electricity-exporting states. As with any project, a hurdle for offshore wind farms is getting the requisite permissions. Shoreside residents may not wish to see the tips of wind turbines peeking over the horizon, much as shoreside residents in Cape Cod and Long Island have killed offshore wind projects for this reason despite their espoused economic and energy benefits. The northern Great Plains (Montana, the Dakotas, and Wyoming), self-dubbed the Saudi Arabias of wind energy, have the potential to supply the United States with all its electricity needs, weather permitting, on land that would take up about 10 percent of the area of just one state. But these states have not yet become the center of wind activity from a lack of a long-distance transmission system to get the electricity to market. If a transmission superhighway were authorized to be built that reached into the northern Great Plains, these states may well take the first steps to fulfill their self-proclaimed slogan.

Germany and Spain, in common with all nations desiring renewable sources of energy, have various subsidy programs in place to support the development of renewable resources. These subsidy programs have made it possible for parts of Germany (Schleswig-Holstein) to receive as much as 25 percent of their electricity from wind. Denmark, once the global center for wind-energy development, reached 25 percent saturation for wind energy and has essentially stopped adding capacity. Twenty-five percent appears to be an upper limit considering the reliability factor associated with wind. Denmark is still heavily involved with wind technology, being a major exporter of hardware (wind turbines) and software (knowledge and expertise) to other nations. A very large potential area for development of European wind energy is not coastlines but offshore waters. There are 150,000 square kilometers (58,000 square miles) of water less than 35 meters

(115 feet) deep available for development with more than enough potential to fulfill the continent's electricity needs, weather permitting. An acceptable location is one with an annual average wind speed of at least fourteen miles per hour; an ideal location is one with a persistent wind speed between twenty-five and thirty-five miles per hour. Like Pickens' project in Texas, a number of European wind projects have been placed on hold.

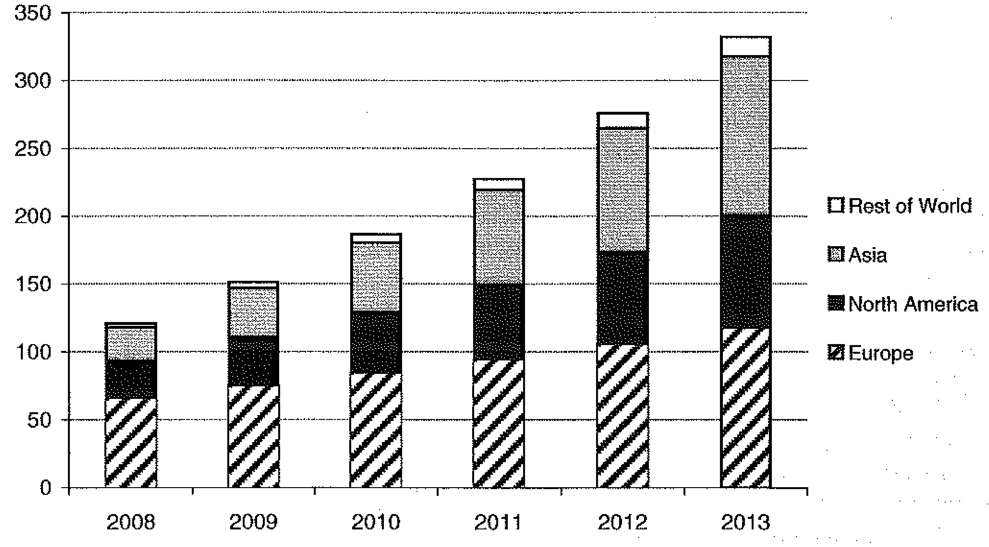
China and India have added a new wrinkle to the story. The Kyoto Protocol sets up the Clean Development Mechanism (CDM), which permits a company of a signatory nation (primarily European) to either reduce its carbon emissions or buy credits via CDMs where carbon emissions can be reduced at less cost than direct investment in carbon-emission controls at the company's facilities. An early example of a CDM was planting trees in developing nations in Africa, South America, and Asia. The carbon reduction of planting trees is a low-cost alternative that could be purchased by a carbon-emitting utility or industrial plant rather than investing in much more expensive means to reduce carbon emissions at their source. A better example today of CDMs is wind-energy development projects in developing nations. In 2009, there were 25 GW of wind power projects in the CDM pipeline including 17 GW in China, 5 GW in India, 1 GW in Mexico, and smaller projects in 18 other developing nations. The irony is that China and India, along with other developing nations, do not participate in the Kyoto Protocol. They do not want to be placed under a mandatory program of reducing carbon emissions because, in their minds, the industrial west is entirely responsible for the buildup of carbon dioxide in the atmosphere. The fact that they now number among the world's heaviest carbon and other pollutant emitters is irrelevant. Yet China, India, and other developing nations freely sell carbon-emission credits to participating Kyoto Protocol signatory nations, which helps to finance their wind and other carbon-reducing projects.

Wind projects are not concentrated in a few countries but are becoming widely dispersed as shown in Figure 9.1 under "Rest of the World," which includes Australia, Japan, Brazil, Canada, and many other nations. The most common-sized wind turbine is 1.5 megawatts, but increasingly 2 and 3.6 megawatt turbines are being installed, with the next generation of 5 megawatt turbines already in the testing stage. Two hundred of these turbines would generate the power of a nuclear or large coal plant, weather permitting.

For wind turbines to be efficiently employed, dispatchers should have a forecast of wind conditions in order to plan the next day's schedule of operation for the utility's generating resources. Unfortunately, dispatchers cannot schedule future production with confidence considering the reliability of weather forecasts. The average output of a wind turbine is only 25–40 percent of its rated output because of variance in wind speeds plus an allowance for downtime for maintenance. Thus 200 GW of wind capacity represent at most 80 GW of conventional electricity-generating plants. Even at the optimistic assessment of 80 GW, wind only represents 1.8 percent of global electricity-generating plant capacity of about 4,500 GW in 2009. Figure 9.3 shows the areas of the world where incremental wind projects are projected to be built.

Although wind projects are worldwide in scope, Figure 9.3 clearly shows that Asia (China and India) will be the area of greatest projected growth. Even if Pickens were to build the world's largest wind farm of 4 GW, the title would be short-lived. China has started construction on the Daliang Wind Station outside Anxi in Gansu Province. When completed, this grouping of six wind farms with an individual capacity of 10–20 GW each may propel China to first place in wind-generated electricity if its announced aggregate output of 100 GW is achieved by 2020. These titanic-sized wind farms will be connected to China's electricity smart grid by a low-loss high-voltage DC transmission system. China has a national goal of building a renewable energy infrastructure in order to become the world's dominant player in wind and solar energy.[11] By 2013, world electricity-generating capacity is expected to be around 4,800 GW. With 330 GW of wind capacity contributing an actual output of 130 GW, wind will contribute 2.8 percent of world electricity-generating capacity. Despite acorns to mighty oaks, the total contribution of wind is not even covering marginal growth in electricity demand. The most it is accomplishing is reducing the growth rate for conventional sources of electrical power. Nevertheless, regardless of the size of the contribution, every watt contributed by wind energy is one less watt that has to be contributed by burning fossil fuels and that much less carbon dioxide and other emissions added to the atmosphere.

Figure 9.3 **Projected Growth in Wind Capacity** (GW)



Objections to Wind Power

Not surprisingly, there has been little opposition to locating wind turbines on farmland, given the long history of windmills on American farms that lasted until the mid-twentieth century. Farming operations are minimally disturbed by the presence of wind turbines, which are normally sited in pastures or along edges of fields, and are viewed favorably by farmers as a source of incremental income. Much of the opposition to developing wind farms comes from suburbanites, real estate developers, and environmentalists for a variety of reasons.

Wind turbines are highly visible. In the 1980s, wind turbines were built with lattice-style structures of 50–300 kilowatt capacity and a rotor blade diameter of 15–30 meters (49–98 feet). In the 1990s, the tubular structure was adopted with turbine capacity of 300–750 kilowatts and a rotor blade diameter of 30–50 meters (98–164 feet). The popular sized GE 1.5 MW wind turbine has 3 blades with a rotor diameter of 77 meters (253 feet) and a hub height in four sizes varying from roughly 60 to 85 meters (197 to 279 feet). As a point of reference, a Boeing 747–400, which can carry up to 436 passengers, has a wingspan just over 211 feet (64.4 meters) and a length just under 232 feet (70.7 meters) and thus can fit within the rotor blade diameter of a large commercial wind turbine. The GE 2.5 MW wind turbine has a rotor diameter of 100 meters (328 feet) and a hub height in 3 sizes of 75, 85, and 100 meters (246, 279, and 328 feet). The 3.6 MW wind turbine has a rotor diameter of 111 meters (364 feet) and its hub height is site specific.[12] No matter what the size, suburbanites do not want to look at them and environmentalists object to locating wind farms in scenic areas or along coastlines.

Some of this opposition can be overcome by designing less obtrusive and/or more pleasing designs, such as foregoing lattice for tubular-style towers and blending a line of wind turbines with the contours of the land. Unsightly transmission lines can be removed by burying them. Some object to the swishing noise of the blade passing through the air, which can be heard within a few miles of a large wind farm and within several hundred feet for an individual wind turbine. Though noise from a wind farm is less obtrusive than normal motor vehicle traffic, the fact that a quiet night is no longer quiet bothers people. To counter this, increasing the separation between a wind farm and residential areas reduces noise levels. Larger wind turbines can be quieter than smaller ones, depending on the speed of the blade tip and the design of a blade's airfoils and trailing edges. Local opposition can be mollified if the citizenry receives a monthly stipend or a reduction in property taxes for permitting a wind farm to be built. Non-local opposition cannot be bought off so easily.

Another objection was locating early wind farms in mountain passes that turned out to be bird migratory paths. Birds were killed when they flew into the rotating blades. Siting wind farms now takes into account bird migratory paths. Even if built in a migratory path, migration is a seasonal phenomenon. Radar can be used to stop the wind turbines when a large flock of birds is about to pass through or near a wind farm. The leading cause of bird fatalities by human interference is not birds flying into wind turbines but into buildings, windows, high-tension lines, communication towers, and motor vehicles, plus fatal encounters with pet cats and pesticides. Wind turbines have the lowest kill rate among these fatal encounters.

Nevertheless, wind turbines pose a hazard for birds that cannot dodge a blade whose tip speed is over 200 miles per hour. A proposed design for wind turbines with no external blade would avoid killing birds. Wind enters a vertical cylindrical structure where airfoils direct the wind against blades on a rotating vertical shaft. The vertical shaft allows the generator to be at ground level for greater ease of maintenance and reduced interference with radio, television, and communication signals. The vertical axis wind turbine is shorter in height than the traditional wind turbine, less obtrusive in appearance, creates less noise from its lower speed of rotation, and has a surrounding wire mesh to prevent birds from entering the turbine. While the vertical axis wind turbine has an optimal wind speed similar to that of traditional wind turbines of 28–33mph, it can operate with wind speeds up to 70 mph versus 50 mph for traditional wind turbines. This higher range of wind speed increases the overall average output from 25–40 percent of rated capacity for traditional wind turbines to 40–45 percent.[13]

As with any utility project, there are a number of organizations a wind farm developer must successfully negotiate with before construction can begin. State governments have boards that require an environmental impact assessment for the wind farm and its transmission lines. Permits are required from land commissions before a project can move ahead. A public utility commission must grant a certificate of need. County- and community-planning boards ensure compliance with zoning ordinances and land use requirements. As with any real estate development, clearing land for access roads and wind turbine foundations must be done in a manner that avoids or minimizes soil erosion. These boards can also address the possibility that a wind farm might interfere with radio and television reception. If the wind project is on land, then the Bureau of Land Management or the Forest Service will be involved along with the Fish and Wildlife Service to ensure minimal hazard to birds and other wildlife.

The views of community groups greatly influence the permit process. Such groups can challenge a site proposal through the court system if they believe that laws, regulations, and legal procedures have not been properly followed. To ensure public support, it is important for project organizers to make the public aware of the benefits of wind power, including any contribution that the wind farm is making in the form of paying local taxes in addition to steps being taken to minimize environmental objections.

Evaluating a Potential Site

While a single wind turbine can have large fluctuations in power output from abrupt changes in wind speed and direction, a wind farm covering a wide area tends to dampen the aggregate impact of shifting winds. Wind patterns can be affected for days from passing storms and weather fronts and for months from seasonal variations (winds are generally more intense in winter and spring). What counts in determining the feasibility of a potential wind farm site is not short-term wind fluctuations or seasonal swings but the average speed throughout the year. The economic return of a wind farm is enhanced if the wind blows more during daytime when electricity is more highly valued. In addition to average annual wind speed, wind patterns near the ground are critical in selecting the height of the hub (center of the rotor). Wind shear is the change in wind speed with height, which is influenced by solar heating, atmospheric mixing, and the nature of the terrain. Forests and cities tend to increase wind shear by slowing the speed of air near the surface. A differential in air speed between the blade's lower and upper sweeps can damage the blade. Wind shear can be greatly reduced with an abrupt change in terrain height such as a sea cliff or mountain ridge. Cliffs and ridges also accelerate wind speed, as do mountain passes.

Financial Incentives

Tax shields to induce investment come in various forms such as accelerated depreciation and tax credits. A tax shield reduces a corporate or personal tax by the tax rate; for a corporation paying a tax rate on its profit of 35 percent, a $100 tax shield is worth $35 in reduced taxes. A tax credit is a far more powerful incentive than a tax shield because a tax credit is a dollar-for-dollar reduction in taxes; a $100 tax credit is worth $100 in reduced taxes as long as the corporation is paying taxes. In 1992, Congress enacted a production tax credit of 1.9 cents per kilowatt-hour for the first ten years of a wind turbine's life. For a tax-paying company, lower taxes can be viewed as a direct subsidy that covers the higher incremental cost of wind energy—up to 1.9 cents per kilowatt-hour more than conventional energy sources. If the installed cost of a wind turbine is no more than 1.9 cents per kilowatt-hour over that of a conventional source of electricity, then the 1.9 cents in tax credits make the wind turbine economically competitive with conventional plants. In the United States, the problem with production tax credits, both at the state and federal levels, is that they normally expire after a short period of time and require frequent legislative renewals, which are not always forthcoming.

When production tax credits expire, those units built before the expiration date keep their tax credits, but new units built after the credits expire do not receive the tax incentive. U.S. production tax credits expired in 1999, were renewed in 2000, expired in 2001, were renewed in 2002, and expired in 2003. This on-again, off-again tax credit has predictable results. Following the expiration of production tax credits in 1999, 2001, and 2003, installations of new turbines fell considerably in 2000, 2002, and 2004. The renewal of the production tax credit in 2004 (effective in 2005) was different in that eligible projects were expanded from wind to include solar, geothermal, micro hydroelectric, open-loop biomass, refined coal, livestock and municipal solid waste, and landfill gas. The renewal in 2004 would have expired at the end of 2005, but the Energy Policy Act of 2005 extended the expiration to the end of 2007. While an improvement, the stop-and-go tax credit still complicates the planning and investment process.[14] However in 2009, as previously mentioned, a 30 percent grant was authorized by the Obama administration that does not expire until 2013, giving the wind and other renewable energy source companies a degree of stability in terms of government support that had been previously lacking.

A successful way to encourage growth in wind energy and other renewable sources is for utilities to offer customers the option to pay a premium on their electricity rates that will support generation of electricity from renewable sources. The utilities enter into a contract to buy the output of a renewable power project at commercial rates that apply to conventional plants. Since this rate cannot economically support an investment in electricity produced from renewable energy, the utility has to find enough consumers willing to make up the difference in the form of a rate premium. Care has to be exercised to ensure that the amount of electricity that carries the premium rate covers, but does not exceed, the capacity of the renewable energy source. In the United States, more than 300 utilities offer their customers a voluntary premium rate that is applied to electricity generated from renewable energy sources. Utilities in the south generally favor solar power while those in the north favor wind power. Some utilities in the United States and abroad give consumers a choice of power supply such as solar, micro hydro, and wind, each with a different premium to cover their respective extra costs.[15] This method does not assure efficiency of operation, however, because the consumer is picking up the entire incremental cost associated with the capital and operating costs of a renewable energy electricity-generating plant.

The approach of the European Union is to set a goal to be attained, not by utilities, but by member nations. The 2001 EU Directive specified an overall EU target to increase renewables' share of electricity from 14 percent in 1997 to 21 percent in 2010. Europeans recognize that conventional power production from coal and nuclear power benefits from state aid, and there is no reason why renewable energy sources should be exempt. Wind energy is subsidized to make it competitive with coal and nuclear energy. The subsidy has only a modest impact on electricity rates when spread across the entire rate base. Germany and Spain went one step beyond and established a quota that had to be filled by wind power, coupled with an associated electricity rate that would spur its development.

Policy directives, consumers voluntarily bearing the extra cost, production tax credits, and quotas with a fixed price have their pros and cons, but they are not as effective as the renewables portfolio standard (RPS) approach. If energy from renewables is desirable because of security of supply or environmental concerns over fossil fuels, then a more forceful approach is warranted than tax gimmicks, appeals to a consumer's environmental conscience, and policy goals. In the United States, a number of states have some form of renewable power requirement where a certain percentage of the power generated by a utility must come from clean, renewable energy. The RPS starts low and slowly increases up to 10 or 15 or 20 percent or more of the utility's portfolio over a reasonable period of time. It is up to the utility to select the most economical form of renewable energy source. The RPS is essentially a quota system without a price. A quota with a set price does not provide an incentive to enhance efficiency. A quota without a set price creates a competitive environment among renewable energy providers to offer electricity at the lowest possible price by enhancing efficiency and improving technology. It is anticipated that a national RPS will be established by the Obama administration as part of its energy package, which would provide the nation with a common goal. Presumably a state could have a higher RPS, but not a lower RPS than that stipulated in federal legislation.

The gap between the cost of electricity generated by conventional and renewable sources has narrowed considerably with the tripling or quadrupling of natural gas prices and the doubling of coal prices in 2004 and 2005. However, the collapse of natural gas prices in the United States in 2009 has lowered electricity rates, and in so doing, taken away from the incentive for alternative energy sources. The gap has been further narrowed by technological progress in lowering the capital and operating costs of generating electricity from renewable energy sources, particularly wind turbines. Wind is clean and free and the cost of electricity generated by wind is not affected by OPEC but only by its capital, insurance, and maintenance costs. Wind farms are a hedge against rising fossil fuel prices and can be built in stages in response to growing demand, quite unlike large coal and nuclear plants that add large increments to capacity that may not be entirely usable during the early years of a plant's life.

Lastly, the wind industry is a source of employment. According to the American Wind Energy Association (AWEA), growth in the number of wind turbines created 35,000 new jobs during 2008, increasing total employment to 85,000. If wind energy provides 20 percent of the nation's electricity by 2030, the wind industry will support an estimated 500,000 jobs and perhaps as many as a million jobs counting indirect jobs such as accountants, computer systems analysts, and those associated with the integration of wind farms with the electricity grid, including the building of transmission lines. According to the European Wind Energy Association (EWEA), the wind industry employed 108,000 people directly and 150,000 in total counting indirect jobs in 2008, double that of 2002. As is also true for the United States, the EWEA cites shortages of project and site managers, engineers, and skilled operations and maintenance personnel. If present projections of wind-generating capacity hold true, direct employment in Europe will be 330,000 by 2020 and 375,000 by 2030, split with 160,000 associated with onshore installations and 215,000 with offshore installations. This suggests that nearly 60 percent of wind turbine capacity will be in offshore waters by 2030.

Small Can Be Beautiful

As with hydropower, wind farms do not have to be large to be effective. Isolated areas that are not connected to electricity grids via transmission lines can be served by hybrid power systems consisting of a local distribution system to supply electricity from small wind farms coupled with diesel generators as backup when the wind is calm. In addition to small wind farms, there is an increasing effort to develop small wind turbines to allow individual homeowners, farmers, businesses, and public facilities to generate their own clean power to reduce electricity bills or for use in areas not served by an electricity grid. Wind turbines for individuals have a capacity of 1–10 kilowatt hours, while intermediate wind turbines of 10–100 kilowatt hours can serve villages and can be augmented by solar power when the sun is shining. Battery storage is a form of backup, but diesel power backup is still needed for those times when the battery has a low charge and the wind is not blowing and the sun is not shining.

SOLAR ENERGY

Like wind, solar energy is also free, but like other free sources of energy, particular conditions apply. Solar power can only be generated during daylight hours, with peak output on clear days when the sun is directly overhead. Several factors affect the efficiency of solar power: cloud cover, which markedly reduces solar output; times of day when the sun is near the horizon (early morning and late afternoon); seasons during which the sun does not rise high in the sky (winter at high latitudes). As with wind, solar power can contribute to power generation, but cannot be relied upon without a backup. Solar power is more expensive and its overall contribution is smaller than that of wind. Solar power has one advantage over wind—it is produced only during daylight hours when electricity demand is highest, reducing the need for peaking generators.

There are two types of solar energy. Thermal solar is a source of hot water that can be used for heating or for making steam to generate electricity. Photovoltaic solar is the direct conversion of solar energy to electricity.

Historical Development

Sunlight sustains life on Earth, and the sun was an object of worship in early religions. The Chinese and Greeks were the first to apply technology to the sun in the 7th and 6th centuries BCE with the "gnomen," a vertical stick or stone in the ground that would trace the sun's shadow to show meal times first and foremost, but also mark the solstices (important for planting and harvesting) and determine latitude and true North. They also began using crude magnifying glasses to focus the sun's rays to light fires for light, warmth, and cooking. The Chinese were the first to use mirrors (reflective metals) to light fires, and later mirrors were used by the Greeks and Romans to light torches for religious processions. In the fifth century BCE, the Greeks incorporated passive solar design in their buildings by allowing the southern sun to penetrate the interiors for warmth in the winter. In 212 BCE, Archimedes focused sunlight with polished bronze shields on a Roman fleet attacking Syracuse and succeeded in setting ships afire (this was successfully repeated in 1973 by the Greek navy setting fire to a wooden boat 50 meters away from the reflectors). During the first four centuries of the Common Era, the Romans improved on Greek passive solar technology practices with large, south-facing windows in public bathhouses to capture the sun's warmth and greenhouses for growing exotic plants. The Justinian Code (529–534) included laws regarding "sun rights" to ensure that houses and buildings had continued access to sunlight after their construction. In the thirteenth century, the Anasazi Indians in the U.S. Southwest built their dwellings in south-facing cliffs to capture the warmth of the winter sun. In 1515, Leonardo da Vinci proposed the use of parabolic reflectors to supply energy for a cloth dyeing factory.[16]

Capturing the thermal energy of the sun in a more dynamic way began with Auguste Mouchout, a French mathematics instructor, who converted solar radiation into mechanical steam power in 1860. The arrival of cheap coal from England stopped further progress in capturing solar power, but he was also able to demonstrate the use of solar energy in pasteurization and making ice. In 1883, John Ericsson, an American, invented a solar-powered steam engine that used parabolic trough construction to concentrate solar energy similar to Mouchout's engine. Ericsson also noted prophetically that in a couple of thousand years, a drop in the ocean of time in his opinion, coal fields will be completely exhausted and the heat of the sun will have to be their substitute. He was off in his timing but right in his concept. In 1878, an Englishman William Adams constructed a reflector of flat silvered mirrors in a semicircle to track the sun's movement and concentrate the radiation on a stationary boiler to heat water. He was able to power a 2.5 horsepower steam engine, much larger than Mouchout's 0.5 horsepower steam engine. He advocated the use of solar energy as a substitute for fuel in tropical countries. His basic design, known as the power tower concept, is still in use today. Charles Tellier, in 1885, installed the first solar-energy system for heating household water on his rooftop. Henry Willsie was the first to build a solar plant capable of storing power for nighttime use at his two electricity generating plants in California in 1904, but was unable to compete with low-cost power from fossil fuels. In 1912, Frank Shuman built parabolic solar collectors near the Nile River capable of tracking the sun. The reflectors produced enough steam to power a series of water pumps totalling 55 horsepower capable of lifting, for the time, an astonishing 6,000 gallons of water per minute a height of 33 feet to irrigate a large tract of desert land. His dream of building 20,000 square miles (!) of reflectors in the Sahara desert for irrigation purposes died when his Nile River installation was destroyed during the First World War. Passive solar buildings became popular during the Second World War when energy became scarce. In the 1950s, Frank Bridgers designed the first commercial building with solar water heating, now listed in the National Historic Register. Giovanni Francia, an Italian, invented the Fresnel reflector in 1964, which can substitute flat glass for curved glass in focusing solar energy. In 1969, a "solar furnace" was constructed in Odeillo, France, featuring an eight-story parabolic mirror.[17]

Capturing solar energy in the form of electricity began with Edmund Becquerel, a French physicist, who studied the photovoltaic (electricity from light). In 1838, he noticed that an electrical current through two metal electrodes submerged in a conducting medium increased when exposed to light but did not pursue the matter further. In 1873, Willoughby Smith, an Englishman, experimented with the photoconductivity of selenium. The first solar cell is credited to an American, Charles Fritts, who coated the semiconductor selenium with a thin layer of gold in 1883 to produce the first working photovoltaic (PV) solar cell.

A PV solar cell is made up of two layers of semiconductor material that can convert sunlight to electricity. One layer has an abundance of electrons and the other a shortage. Sandwiching these together forms an electrical field at the interface, which acts as a battery when exposed to sunlight. PV solar cells produce direct current, which has to be converted to alternating current for home use or feeding into an electricity grid. However, the high cost and low efficiency of 1 percent for converting solar energy to electricity left the Fritt's idea dormant until 1941 when another American, Russell Ohl, used silicon to improve the conversion rate to 5 percent at a far less cost. Russell Ohl received a patent for what is recognized as the first modern solar cell. In 1954, three scientists at Bell Laboratories were able to design a silicon solar cell with a greater conversion rate of solar energy to electricity of 6 percent along with another reduction in cost, opening the door to the commercialization of solar cells. The first commercial solar cells made their debut in 1956 to power radios and toys but were very expensive at $300 per watt. AT&T built the first solar arrays to power the earth satellite Vanguard I launched in 1956. Hoffman Electronics improved the conversion rate of silicon cells to 10 percent in 1960. In 1963, Japan built the largest ground-based PV array installation of 242 watts with a storage battery to supply electricity for a lighthouse. The energy crisis in 1973 provided the incentive to increase funding on solar technology with the result that the price of solar cells dropped dramatically to about $20 per watt (today it is $4–6 per watt). In 1973, the University of Delaware built "Solar One," a roof-installed integrated photovoltaic/thermal hybrid system that supplied heated water to a home as well as electricity. The excess output during the day was sold to a utility that supplied the home with electricity at night and during times of cloud cover.

Thermal Solar Energy

Thermal solar energy can heat water for space heating, household appliances, swimming pools, and for various commercial and industrial processes. Solar water heaters with copper collector tubes in a glazed housing can be installed on the roofs and sides of homes most exposed to sunlight. When the sun is shining, water is pumped through the collector and the heated water is stored in a tank. A thermosiphon solar water heater has the storage tank above the collector tubes, eliminating the need for a pump. Although thermal solar energy is associated with warming a house, heated water can drive an absorption or desiccant air-conditioning system for cooling a house. For colder climates, a water/glycol mixture is pumped through the collector, which then requires a heat exchanger to heat water for appliances and space heating. Backup substitute power is required for cold, cloudy, blustery days when snow and ice cover the thermal panels.

Harking back to the days of the Greeks and Romans, buildings can be designed for passive solar energy by having large south-facing windows complemented with building materials that absorb and slowly release the sun's heat. There are no mechanical aspects to passive solar heating, and a well-designed system can significantly cut heating bills. Passive solar designs also include natural ventilation for cooling during hot weather. Hybrid lighting concentrates sunlight and feeds it through fiber optics into a building's interior. "Hybrid" means that a backup power source for interior lighting is necessary for times of little or no sunlight, and certainly for nighttime illumination. Thermal solar output for heating water, including a small portion for electricity generation, was nearly 70 GW in 2001. China led with 22.4 GW of solar thermal capacity followed by the United States with 17.5 GW, Japan with 8.4 GW, Turkey with 5.7 GW, and Germany with 3.0 GW.[18] This dwarfed the installed output of 1.1 GW of photovoltaic output at that time (in 2007, photovoltaic output was about 8 GW).

Solar thermal energy can also heat water for conversion to steam for driving turbines to generate electricity. The types of thermal solar power systems that can generate electricity are parabolic troughs, power towers, and dish/engine systems. These technologies are normally hybridized with fossil fuel (natural gas) to maintain electricity output when the sun is not shining or covered with clouds. This gives the system the necessary reliability required by dispatchers and enhances the economic performance of the system (the generator is producing revenue whether or not the sun is shining). Natural solar power provides 2.7 megawatts per square meter per year. While this may sound impressive, it is actually a low rate of energy transfer considering that this is over a year's time. Thus, solar thermal systems require a great deal of area for mirrors to collect and concentrate the requisite solar energy. However, the land area does not compare unfavorably with coal-fired plants when mining and storage areas are taken into consideration.[19]

Solar thermal energy for electricity generation requires a location where there is sunlight much of the time and sufficient available space for mirrors. The ideal location is a desert. The first system to commercially convert solar thermal energy to electricity was built in the 1980s in the Mojave Desert in California. Nine solar thermal electricity-generating plants have a combined output of 354 megawatts (one-third the output of a large coal-fired or nuclear power plant), the world's largest installation of solar power. Trough-shaped parabolic mirrors automatically follow the sun and focus the sun's rays at thirty to sixty times their normal intensity on a receiver pipe filled with synthetic oil. The oil is heated to 735°F and passes through a heat exchanger to produce steam for a conventional steam turbine electricity generator. Natural gas serves as a supplemental fuel for cloudy weather and nighttime operation.[20]

The modern power tower, also developed in California, stores solar energy in the form of molten-salt. A circular field array of heliostats (large mirrors) individually tracks the sun. The heliostats focus sunlight on a central receiver mounted on top of a tower to heat molten salt, such as a mixture of sodium and potassium nitrate, to 1,050°F for storage in the "hot" tank. As power is needed, molten salt flows from the hot tank through a heat exchanger to produce steam for electricity generation. Then, it travels to the "cold" tank, where it remains molten at 550°F until needed for heating in the tower. Depending on the size of the hot tank and its insulation properties, a hot tank can supply energy to generate electricity for some hours after sunset, an advantage over trough-shaped parabolic mirrors. Moreover, the system is more reliable because dispatchers can depend on the system to produce power even when clouds temporarily cover the sun by generating electricity from energy stored in the hot tank. To further enhance reliability, the system can be hybridized with a fossil fuel, such as natural gas, to produce power when needed by a dispatcher at any time.

Trough-shaped parabolic mirrors and power towers require water to generate steam, a commodity in short supply in a desert, but no water is required for the dish/engine solar energy system. Parabolic dish-shaped mirrors, mounted on a single support frame, focus solar energy on a receiver to heat a transfer fluid to nearly 1,400°F. The heated fluid transfers its heat to a gas such as hydrogen or helium to power a Stirling engine, which is similar in construction to an internal combustion engine, or to a Brayton engine, which is similar to a gas turbine engine (sometimes referred to as a micro-turbine). In neither case is there combustion; the engines run off the energy of the heated gas and drive an electricity generator. Solar dish engines have the highest efficiency of thermal solar systems, converting nearly 30 percent of solar energy to electricity. Trough-shaped parabolic mirrors and power towers best serve an electricity grid whereas solar dish engines best serve isolated areas beyond a power grid. However, there is nothing that precludes connecting dish engine arrays to a grid.

The latest idea, based on one first advanced by Leonardo da Vinci, is a solar power tower shaped like a chimney that directs hot surface air up to cooler air at higher altitudes. One company plans to build such a tower that will direct heated surface air up the circular tower to cooler air almost 3,300 feet (1,000 meters) above the Australian outback. The power driver is the air temperature differential between the bottom and the top of the tower. The tower is surrounded by sunlight-absorbing material that further heats the incoming air. Air rushing in the bottom of the tower passes through wind turbines that can generate up to 200 megawatts of rated capacity, enough to supply electricity to 200,000 Australian homes.[21] Table 9.1 lists the thirteen largest thermal projects in existence or under construction.[22]

Photovoltaic Energy

The earth receives an average of 1,367 watts of energy per square meter (about 11 square feet) at the outer edge of the earth's atmosphere. The atmosphere absorbs and reflects most of the X-ray and ultraviolet radiation, reducing the energy that reaches sea level at high noon on a clear day to a maximum of about 1,000 watts per square meter. One hour's worth of solar energy striking the earth is greater than all the energy consumed by the world's population in one year. Desert land 100 miles on a side (10,000 square miles, which is equivalent to 9 percent of the area of the state of Nevada) could generate enough electricity to supply the United States, weather permitting (the Southwest could become the Saudi Arabia of solar power!). However, the intent is not to concentrate the nation's solar power in one location, but to install solar power plants on rooftops and over parking lots throughout the nation to reduce reliance on electricity from conventional sources.[23]

Many nations are pursuing the solar option and research is being conducted under a wide assortment of public and private programs sponsored by governments, universities, and private enterprises. The objective is to make electricity from solar power competitive with conventional sources by reducing front-end costs such as material costs for semiconductors, manufacturing and installation costs of solar arrays, and enhancing efficiency. The greater the efficiency in converting sunlight to electricity, the smaller the solar array has to be to deliver a given amount of electricity.

Most commercial PV solar cells are made of crystalline silicon cut in wafers as thin as 200 microns, usually between two and three square inches (12.5 to 20 square centimeters) in area. Single-crystal PV cells are grown and have a commercial efficiency that ranges between 15–18 percent in converting solar energy to electricity. Solar cells have a higher efficiency if surrounded

Table 9.1

World's Thirteen Largest Solar Thermal Power Projects

Location	Size	Type	Solar Co.	Utility	Start
Mojave Desert, US	500 MW to be expanded to 900 MW	Power Tower	BrightSource Energy	Pacific G&E	2011
Mojave Desert, US	500 MW possibly to 850 MW	20,000 Parabolic Dishes over 4,500 acres	Stirling Energy	San Diego G&E	2011
Upington, South Africa	100 MW possibly to 600 MW	Power Tower	Eskom	Eskom	Not yet finally approved
Mojave Desert, US	553 MW	1.2 million mirrors, 317 miles vacuum tubing, 6,000 acres	Solel	Pacific G&E	2011
California, US	400 MW	3 Power Towers	Solar Partners		Not yet started
Mojave Desert, US	310 MW	400,000 mirrors on 1,000 acres		Southern California Edison and Florida Power & Light	World's largest operating built 1984–1991, Solar Energy Generating Systems (SEGS)
Seville, Spain	Now 11 MW being expanded to 300 MW	Power Tower	Abengoa and ALTAC		2013
Florida, US	300 MW	Flat Fresnel Reflectors substitute for Parabolic mirrors		Florida Power & Light	2011
Arizona, US	280 MW	Mirrors on 1,800 acres	Abengoa	Arizona Public Service	2011
Negev Desert, Israel	250 MW			Gov't of Israel	Seeking bids
Mojave Desert, US	250 MW	500,000 parabolic troughs on 2,000 acres		Florida Power & Light	2011
California, US	177 MW	Fresnel Reflectors	Ausra	Pacific G&E	2010
Mildura, Australia	154 MW may be expanded to 5,000 MW by 2030	Power Towers	Solar Systems	TRUenergy	2013 for the 154 MW

by cool rather than warm air. The space program normally uses more expensive PV cells made of gallium arsenide, whose efficiency in transforming solar energy to electricity can exceed 30 percent.[24] Multicrystalline PV cells depend on a less-expensive melting and solidification process, but have a marginally lower commercial efficiency of 14 percent. An even lower-cost solar cell is a film of extremely thin layers of PV semiconductor materials such as amorphous silicon, copper-indium-gallium-diselenide, or cadmium telluride, deposited on a backing of glass, stainless steel, or plastic. While cheaper to make, thin-film PV arrays have a lower efficiency that ranges between 7–13 percent, so they have to cover more area to produce the same output than conventional solar panels. The advantage of thin films is avoiding the glass covering and mechanical frames of conventional solar panels. Thin films on a plastic covering can be made to look like roofing material and designed to fulfill the twin roles of protecting the roof from weather plus generating electricity from the sun. The savings in not having to install roofing reduces the cost of the solar power system. There is also research on employing nanotechnology to produce organic solar cells of molecular polymers and other esoteric materials. Progress in thin films technology has spurred their growth from 6 percent of PV capacity in 2005 to 13 percent in 2007; the remaining is primarily wafer design.

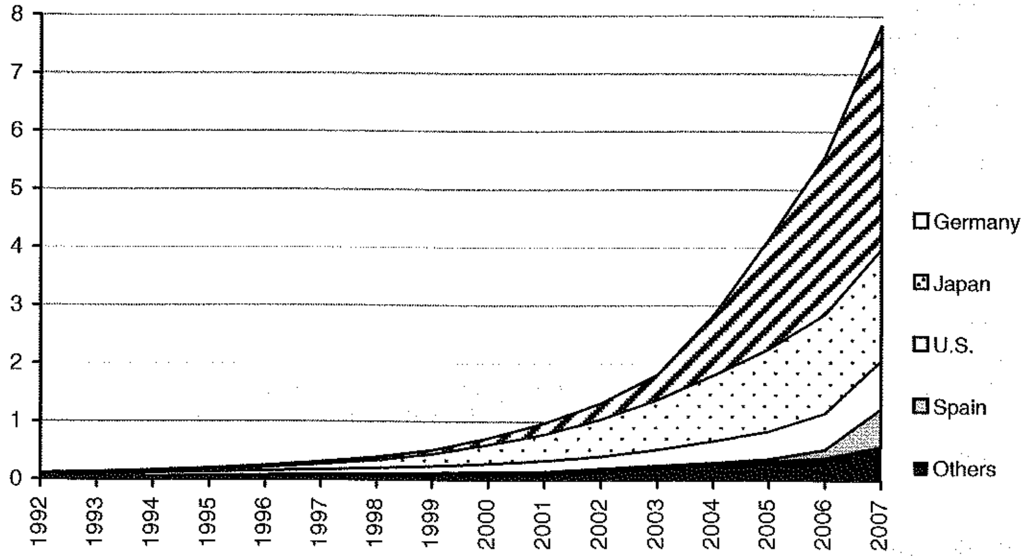
A PV, or solar, cell is the basic building block, small in size, and capable of producing 1 or 2 watts of power. These are combined into larger units, called modules or panels, which produce 50–300 watts of power, which are then joined together to form solar arrays sized to meet the desired power output. Solar arrays are particularly useful for serving isolated buildings in sunny climates such as lodges in national parks, lighthouses, and other buildings and facilities far from an electricity grid. Smaller solar modules can light signs, streets, gardens, pools, and provide power for remote telephones or automatic teller machines, or any need with similar power requirements. These applications normally have an associated battery that is charged by day in order to supply power at night or during times of inclement weather.

Solar arrays are given serious consideration by government bodies to help launch economic development in areas too remote and/or sparsely populated to justify building an electricity grid. An independent solar-power system, with a battery to store electricity for times of cloud cover or at night, in isolated locations obviates the need for building a generation, transmission, and distribution system. A good example of this is a $48 million solar-power project on the island of Mindanao in the Philippines. The project, funded by the Spanish government and built by BP Solar, will supply electricity to 400,000 people in 150 villages plus provide electricity for irrigation and drinking water systems and for schools and medical clinics.[25]

Solar power can bring electricity to a remote area at less cost than building a conventional generation, transmission, and distribution system, including the purchase of normally imported fuel. Solar and wind power, either singly or together, with a diesel backup, are viable means of supplying electricity on a local or distributive basis to the 2 billion people who live in isolated communities far from electricity grids or in areas of low population density. One of the chief benefits of introducing hybrid renewable electricity to remote locations is improving the health of the people. Females in some parts of the world spend nearly every waking hour collecting and transporting dung and wood on their heads or backs for cooking and heating. Some have to walk twenty miles a day, rising early in the morning and going to bed late at night, ruining their health in the process. Moreover, cooking with biomass in closed environments is a major health hazard that shortens life expectancy. Electricity from renewable sources eliminates these time-consuming and onerous tasks and their adverse health consequences. Electricity allows women to sleep longer, improving their health; and, when they are awake, have the energy to improve their lifestyle.

If an electricity grid is available, solar arrays can be connected into the grid for a power sup-

Figure 9.4 **Growth in Solar Photovoltaic Power** (GW)



ply by night or on cloudy days, eliminating the need for a battery. Arrangements can be made for excess production of a solar array to be fed into the grid, the revenue of which can be part of the economic decision to install a solar power system. In addition to the solar panels, the capital investment also includes the cost of a mounting structure and the installation of the array, an inverter to convert the direct current output to alternating current, a storage battery for off-grid solar systems, along with a charge controller for battery operation or modifications to an existing electricity grid to allow the sale or purchase of electricity.[26] As Figure 9.4 shows, growth in solar power is exponential, similar to wind, but in comparing Figure 9.4 with Figure 9.1, solar provides less than 10 percent of wind power's contribution.

Three-quarters of the 50 percent growth in solar PV power in 2007 took place in Germany and Spain, and the figure is 90 percent by adding in Japan and the United States. The two major subdivisions of solar power are off-grid and grid-connected. Off-grid installations are at remote locations where homes and buildings are not connected to an electricity grid. Off-grid installations serve remote telecommunications stations, navigational aids, and other needed functions. Solar-powered emergency phones can be found along major highways. Grid-connected installations also serve homes and buildings, but are also connected to an electricity grid for service when the sun is not available and for sale of unneeded electricity back into the grid. In 1992, about 75 percent of installations were off-grid and 25 percent were grid-connected. In 2007, the ratio was 5 percent off-grid and 95 percent grid-connected. Table 9.2 shows the thirteen largest PV projects. The United States plays a less dominant role in PV projects than thermal projects listed in Table 9.1.

The development of solar power, as with wind, started in the United States (California, to be precise) as a result of PURPA legislation. Since the mid-1990s, Japan and Germany have become centers of solar energy development. The largest suppliers of PV cell production are located in Japan with a 38 percent share, Germany 35 percent, United States 11 percent, Norway 6 percent, and Spain 5 percent. The largest corporate suppliers of PV cell production are Q-Cells (Germany) with a 16 percent share, Sharp (Japan) 15 percent, Kyocera (Japan) 9 percent, Sanyo (Japan) 7 percent, Deutsche/SolarWorld (Germany/U.S.) 6 percent, Scancell (Norway) 6 percent, Mitsubishi (Japan) 5 percent, First Solar (U.S./Germany) 5 percent, and Isofoton (Spain) 4 percent. The largest suppliers dominating the solar photovoltaic grade silicon market are Wacker (Germany), REC Solar Grade Silicon and Hemlock Semiconductor (U.S.), and Tokuyama (Japan). The U.S. is a major provider of PV grade silicon in the PV supply chain. A large number of companies are involved with other aspects of solar power including supplying semiconductor materials, producing PV modules, and installing solar panel arrays. In addition, there is a great deal of entrepreneurial effort by companies trying to establish a niche in this emerging business.

Table 9.2

World's Thirteen Largest Solar Photovoltaic Power Projects

Location	Size	Solar Co.	Utility	Start
New Mexico, US	300 MW	New Solar Ventures and Solar Torx on 3,200 acres		2011
Arizona, US	280 MW	Abengoa on 1,900 acres	Arizona Public Service	Not yet finally approved
Victoria, Australia	270 MW	Solar Systems (company intends to build 270,000 MW to fulfill Australia 20% goal for renewable by 2020)	TRUenergy	2013
California, US	80 MW	Cleantech and California Construction Authority on 640 acres		2011; California also has legislation calling for solar panels to be installed on 1 million roofs by 2018
Leipzig, Germany	40 MW	Juwi Solar		2009
Murcia, Spain	20 MW	120,000 PV panels on 247 acres	Atersa	Operating since 2008
Alicante, Spain	20 MW	100,000 PV panels	City Solar	Operating since 2007
Sinan, Korea	20 MW	109,000 PV panels	SunTechnics	Operating since 2008
Nevada, US	14.2 MW	90,000 PV panels on 140 acres	Sunpower	Operating since 2008
Salamanca, Spain	13.8 MW	70,000 PV panels	Kyocera	Operating since 2007
Murcia, Spain	12.7 MW	80,000 PV panels	Ecostream	In operation
Bavaria, Germany	12 MW	1,400 sun-tracking PV panels	Solon AG	Operating since 2006
Alentejo, Portugal	11 MW	52,000 PV panels on 150 acres		Operating since 2007

Significant government monies are being invested in the development of solar power. In 2007, the four nations that spent the most for solar energy research and development were the United States ($138 million), Germany ($61 million), Japan ($39 million), and South Korea ($18 million). Japan, Germany, United States, and other nations offer incentives for individuals and businesses to install solar energy. Like those provided for converting to wind and other alternative sources of energy, these come in various forms such as a direct grant or rebate paid to the individual or business for installing solar panels, various tax benefits, soft loans at below market interest rates and long payout periods, the right to sell excess production back to the utility at above-market rates (feed-in tariffs), and sustainable building standards that require installing PV panels. In the United States, most states have some sort of program to encourage the development of solar energy, ranging from personal, corporate, sales, and property tax exemptions plus loan and grant programs as a means of inducing homeowners to install solar power. Significant rebates of the order of 50 and 60 percent are offered by various states such as New York and New Jersey. In addition, the government has a production tax credit that can be applied against corporate taxes for companies that install solar power and other forms of renewable energy plus, as with wind, direct grants provided by the 2009 American Recovery and Reinvestment Act.

Economics of Solar Power

The economics of solar power depend on many variables. For example, an energy-efficient 2,000-square-foot home needs about 2 kilowatts of output from a solar array mounted on the roof. If the cost of installation is $16,000 and if there is a rebate available for $8,000, the net cost to the consumer is $8,000. The amount of electricity that the solar array can produce is 100,000 kilowatt hours over its twenty-five-year life, assuming that the sun is shining an average of 5.5 hours per day (2 kilowatts per hour × 5.5 hours per day × 365 days per year × 25 years). The 5.5 hours per day takes into consideration reduced output when the sun is near the horizon and during times of cloud cover. At higher latitudes, three hours per day might be a closer approximation for the equivalent of sunlight directly overhead with no cloud cover. If the average cost of electricity over the next twenty-five years were ten cents per kilowatt hour, then the avoidance of the need to purchase 100,000 kilowatts from a utility would equal the net investment of $10,000, including accrued interest. Without the rebate, there is no economic justification for installing solar power.

Solar power works better if electricity rates are based on time-of-day metering when rates track actual demand. This would improve the economics of solar power immensely since the day rate for electricity is much higher than the night rate, reflecting marginal rates charged by base-load electricity providers. If electricity rates during daylight hours were sixteen cents per kilowatt hour, then the investment of $8,000 (after the rebate) will generate savings of $16,000 in avoided electricity purchases over a twenty-five-year period, providing a 2.8 percent return on the investment. If there were no rebate, the savings would only compensate for the investment, assuming the money has no time value. If it is profitable to install solar power, then one can consider oversizing the array and selling the excess power back to the utility. Regardless of the economic analysis, one may still choose solar power just for the satisfaction of having a home that does not require burning a fossil fuel or relying on nuclear power.

Installing a 454-kilowatt solar array for Monmouth University in New Jersey had a capital cost, including installation, of $2,860,000. A substantial rebate was available from the state of New Jersey in the amount of $1,715,000 (60 percent of capital cost). This reduced the capital investment to $1,145,000. Table 9.3 shows the economic analysis of the installation assuming a cost of purchase of ten cents per kilowatt-hour, with 3 percent escalation over the twenty-five-year life of the solar panel.

The net capital investment of $1.1 million earns a healthy return, primarily in the form of avoided electricity purchases. Any hike in electricity rates above ten cents per kilowatt-hour, which occurred as a consequence of much higher natural gas prices for the utility, increases the rate of return on the investment. As the analysis plainly shows, the internal rate of return is positive only because of the significant commitment on the part of the government to support the development of solar power. A review of the project in 2009 showed that its profitability was greater than originally anticipated because of subsequent hikes in electricity rates. The solar installation provided a fixed electricity rate that lowered the overall cost of electricity. A new building on campus was not fitted with solar panels pending a study on the feasibility and economics of a thin-film solar installation that would be applied directly to the building without the need for frames to hold solar panels.

Table 9.3

Economic Analysis of Actual Solar Energy System

	Aggregate Savings (Costs) over 25-Year Life of Project
Avoided Electricity Purchases	$2,415,000
Avoided Transformer Losses	$50,000
Estimate of Sales of Excess Electricity Back to Utility First 4 Years Only	$315,000
Maintenance of Solar Energy System and Roof	($110,000)
Aggregate Savings	$2,670,000
Cost of System net of Rebate	$1,145,000
Internal Rate of Return over 25 Year Period	8.3%

One of the over 300 utilities that offer electricity from renewable energy to consumers is Arizona Power Service. Located in the Southwest, where the company can take advantage of the 300 days of sun, and with plenty of available desert land for installing solar arrays, the utility has become a leader in promoting solar power to its customers. The company intends to build two thermal solar systems totalling 0.6 GW and offers homeowners a free installation of rooftop solar panels that fixes the cost of their electricity for the next twenty years. The company's objective is to make Arizona the "Solar Capital of the World."[27]

Further government support for solar power occurred at the end of 2005 when the California Public Utilities Commission unveiled a plan to install 3 gigawatts (3,000 megawatts) of capacity over the next eleven years. This plan would double the existing global solar power capacity and would supply 6 percent of California's peak electricity demand. The California Solar Initiative provides $3.2 billion in rebates over the next eleven years with the objective of installing solar panels on 1 million homes and public buildings. Funding would also be eligible for solar water heating along with other solar power technologies. The new initiative is actually an expansion of an existing program that adds a surcharge to consumer utility bills with the proceeds dedicated to rebates for solar power installations. In 2009, Public Service Electric & Gas of New Jersey announced a $0.5 billion plan to place small solar panels costing $1,000 each on telephone poles and rooftops in equal numbers to feed directly into the grid. The plan will add about 80 megawatts of power by 2013, making New Jersey second to California in solar-power generation. The U.S. Bureau of Land Management is examining 1,000 square miles of land on twenty-four tracts of public land in the Southwest to identify a potential site of three square miles for the generation of 100 GW of solar power (present U.S. output is less than 1 GW!). Four solar power plants (1 solar array and 3 thermal) are under review for construction in Nevada and California totalling 2.4 GW. Progress in obtaining regulatory approval is impeded over species protection, availability of water for thermal solar projects, and the greatest barrier of them all, a maze of multiple government agencies' regulations with overlapping jurisdictions. Things are not much better on the state level—regulatory requirements are as much an impediment for adding renewable energy capacity as they are for fossil fuels.

One idea on the table is to convert 30,000 square miles of public lands into thin-film module arrays for the generation of 2,940 GW. This would require an increase in thin-film module conversion rate of solar energy to electricity from the present 10 percent to 14 percent and another 16,000 square miles for thermal solar systems with an increased conversion rate from the present 13 percent to 17 percent to generate 558 GW, plus the building of 100,000–500,000 miles of new high-voltage DC transmission lines to connect the Southwest with the nation's electricity grid. The cost of electricity will be near current rates if the indicated conversion-rate improvements can be achieved. Such a system could provide nearly 70 percent of the nation's electricity by 2050 and could be further expanded to provide 100 percent by 2100.[28]

GEOTHERMAL ENERGY

Geothermal energy, from the Greek words *geo* (earth) and *therme* (heat), takes advantage of hot water or steam escaping from hot spots in the earth. Geothermal sources are located where magma is relatively close to the surface of the earth and where the rock above the magma is porous and filled with subsurface water with access to the surface. Geothermal sources are found near tectonic plate boundaries that are separating (the rift valley in east Africa and in Iceland) or colliding creating subduction zones (Japan) or sliding by one another (California). Geothermal energy sources are also found near volcanoes (Mount Vesuvius in Italy, the island of Hawaii, and the caldera at Yellowstone), where magma protrusions lie relatively close to the earth's surface. The Maoris in New Zealand and Native Americans used water from hot springs for cooking and medicinal purposes for thousands of years. Ancient Greeks and Romans had geothermal heated spas. The people of Pompeii, living too close to Mount Vesuvius, tapped hot water from the earth to heat their buildings. Romans used geothermal waters for treating eye and skin disease. The Japanese have enjoyed geothermal spas for centuries.

The earth's crust insulates us from the hot interior of the mantle. The normal temperature gradient is about 50°F–87°F per mile or 17°C–30°C per kilometer of depth and higher where the crust is relatively thin or near plate boundaries and volcanoes. Magma trapped beneath the crust heats up the lower rock layers. If the hot rock is porous and filled with continually replenished subsurface water with access to the surface, then the result is fumaroles of escaping steam and hot gases, geysers of hot water, or pools of boiling mud. As a geothermal source, the earth becomes a boiler and escaping hot water and steam, called hydrothermal fluids, are tapped for hot spring baths, heating greenhouses (agriculture), heating water for marine life (aquaculture), space heating for homes, schools, and commercial establishments, heating streets and sidewalks to prevent ice formation, and as a source of hot water for industrial use or steam for generating electricity. Some cities have district heating using geothermal hot water to heat an entire area, best exemplified in Reykjavik, Iceland, where 95 percent of the city receives hot water from geothermal sources.

There are three types of geothermal power plants for generating electricity. The first is a dry-steam geothermal reservoir in which emitted steam directly spins a turbine. These are relatively rare and were the first dedicated to generating electricity. One in Tuscany has been in operation since 1904 and The Geysers, 90 miles north of San Francisco, has been in operation since 1960. The Geysers represents the largest single source of tapped geothermal energy in the world and generates enough electricity to supply a city the size of San Francisco. A falloff in steam pressure in the 1990s was successfully countered by water injection to replenish the geothermal reservoir. Injected water was waste treatment water from neighboring communities, an innovative and environmentally safe method of disposal. Some thought has been given to tapping the world's most productive source of geothermal energy, Yellowstone, the caldera of a supervolcano that last erupted 600,000 years ago. (Another eruption of that magnitude would wipe out half of the United States and emit an ash cloud large enough to send the planet into a "volcanic" winter.) But Yellowstone, as a national park, cannot be commercially developed.

The second and most common form of geothermal power plant is driven by geothermal reservoirs that emit hot, pressurized water between 300°F–700°F. The drop in pressure inside a separator allows the liquid to flash to steam, which is then directed into a turbine. Any gases in the geothermal water such as carbon dioxide, hydrogen sulfide, and nitrous oxides pass to the atmosphere, but these are a tiny fraction of the emissions from a coal-burning plant with an equivalent power output. Water and steam remaining after flashing and passing through a turbine are usually reinjected to replenish the water in order to maintain the reservoir's pressure. If reservoir pressure can be maintained, then geothermal becomes a sustainable source of nearly nonpolluting clean energy.

Shallower sources of geothermal energy in which the water temperature is between 250°F–350°F require a binary power plant where a heat exchanger transfers the heat of the geothermal water to a second or binary fluid such as isopentane or isobutane. The binary fluid boils at a lower temperature than water and its vapors pass through a turbine and are then condensed to a liquid for recycling. Binary plants are closed systems in which the hydrothermal fluid, along with any entrapped gases, is reinjected into the reservoir. A binary system may be necessary for water with a high mineral content to prevent forming a harmful scale on the turbine blades. Hybrid plants, part flash and part binary, are also available such as the one that supplies 25 percent of the electricity for the island of Hawaii.

As of 2005, there were 490 geothermal power plants with 9 gigawatts (GW) of installed capacity, equivalent to the production of nine large-sized nuclear or coal-fired plants, enough to supply the electricity needs of 9 million people.[29] The United States leads with 2.9 GW, mostly in California and Nevada, whose 209 operating plants supply 0.5 percent of the nation's energy needs. The second largest producer is the Philippines with 57 operating plants of 1.9 GW of capacity sufficient to meet 19 percent of the nation's electricity demand. The third largest is Mexico with 36 operating units of 0.95 GW, representing 3 percent of the nation's electricity. The fourth largest is Indonesia with 15 operating plants of 0.8 GW sufficient to satisfy nearly 7 percent of the nations' electricity needs. Italy is the fifth largest producer with 32 plants of nearly 0.8 GW of electricity or 2 percent of the nation's electricity needs (one center of activity is near Mount Vesuvius on the outskirts of Naples). Other nations have smaller outputs, but their generating capacities make a meaningful contribution in satisfying the nation's electricity needs such as El Salvador (22 percent of electricity is geothermal), Kenya (19 percent), Iceland (17 percent), Costa Rica (15 percent), and Nicaragua (10 percent). It is interesting to note that Central America is largely dependent on renewable sources, hydro and geothermal for electricity generation. Thermal uses, distinct from generation of electricity, total another 16 thermal GW for hot springs, agriculture and aquaculture, and district heating.[30] Geothermal heat pumps use the constant underground temperature either for cooling or heating residences. Heat pumps are effective over a limited range of temperatures and require supplemental cooling and heating to handle more extreme variations in temperature.

Geothermal sources are limited primarily to porous hot rock permeated with subsurface water that can escape to the surface. If water is trapped by a cover of impermeable caprock, then the geothermal reservoir must first be discovered before it can be exploited. The same technology for discovering oil fields and drilling wells to tap oil and natural gas reservoirs can be applied for discovering and developing geothermal reservoirs. The future of geothermal energy is limited in so far as current efforts are, for the most part, restricted to developing known sources of geothermal energy, not in discovering new ones.

Hot rock underlies the entire crust. Its usefulness is a matter of depth and whether it is porous rock filled with subsurface water. But the presence of subsurface water and porous rock is no longer necessary. The feasibility of drilling two wells deep into the earth's crust to reach hot rock, and then fracturing the rock separating the two employing methods practiced by the oil industry, has been demonstrated. Water is then pumped down one well under pressure and forced through the fractured hot rock, where it is heated and rises to the surface via the other well as pressurized hydrothermal fluid. This can be flashed to produce steam and drive electricity generators or heat another liquid medium in a hybrid plant.

Hot rock from a magma protrusion of up to 570°F was discovered two and three-quarter miles below the surface in southern Australia. Geodynamics, a start-up company that raised $150 million in capital, has drilled two wells 14,000 feet down to the hot granite. These wells, when fractured to allow the flow of water from one well to the other, will be able to generate geothermal energy. A small generator is scheduled for completion in 2009 followed by a larger one. It is hoped that these generators will establish the feasibility of generating geothermal electricity on a commercial basis. If successful, large-sized electricity generators will be installed with the possibility of supplying a potential of 10 GW of electricity. A transmission system would have to be built to connect the geothermal-generating plant to the nation's electricity grid. It is possible that this hot rock formation may one day supply most of Australia's electricity needs.[31]

Another geothermal project had a far different outcome. The Swiss Deep Heat Mining Project near Basel, Switzerland, was to pump water down three-mile deep boreholes to hot rocks of 200 degrees Centigrade. The returning superheated steam would be sufficient to supply electrical power to 10,000 homes and hot water heat to another 2,700 homes. The project, partly backed with financial support by the Swiss government, was considered a safe and sustainable alternative to a nuclear power-plant project opposed by the Swiss people. Basel is prone to earthquakes, with one in 1356 strong enough (6.5 on the Richter scale) to raze the city. Pumping water down the boreholes was held responsible for setting off tremors measuring 3.3 on the Richter scale up to ten miles away from the site. The project was suspended. State prosecutors began looking into the possibility of criminal negligence on the part of the promoters despite support from the Swiss government.[32] Nevertheless, there are a number of geothermal projects in various stages of development in India, Nevada, and California.

A more esoteric idea is to mine heat from magma as a geothermal ore in places where it is accessible by current drilling technology. For this, a hole is drilled through the crust and a sealed pipe with a concentric inner pipe is thrust into the magma. Water is pumped down the inner pipe and is transformed into high-pressure hydrothermal fluid by the magma surrounding the bottom of the sealed pipe. From there, the hydrothermal fluid flows up the outer pipe to the surface to be flashed to steam to power electricity generators. A major obstacle to overcome is drilling all the way through the crust. The deepest bore hole ever drilled was in Russia 7.5 miles into crust 30 miles thick. Even if a bore hole were drilled into magma, precautions would have to be taken to prevent creating a mini-volcano if magma escapes to the surface. Another major obstacle is finding materials that can withstand the extreme high temperatures, pressures, and corrosive properties of being thrust into magma.[33] But if the inner heat of the planet could be tapped, geothermal energy could conceivably satisfy the world's electricity demand.

OCEAN ENERGY

The oceans cover over 70 percent of the earth's surface and represent an immense reservoir of energy in the form of tides, currents, waves, and temperature differentials. Tides result from the gravitational interaction of the earth and the moon, with about two high and two low tides each day. The time between high tides is twelve hours and twenty-five minutes. The shift in maximum power output on a daily basis, while predictable, may not correspond to the timing of peak demand for electricity. Tides are also affected by the relative placement of the sun and moon with respect to the earth, which causes spring (maximum) and neap (minimum) tides. The elliptical path the earth traces around the sun, plus weather and other influences, affect tides, as does the topography of the shoreline. Unfortunately, coastal estuaries that can create tidal rises of up to fifty feet are located at high latitudes, far from population centers. Tidal power output must be viewed as a supplemental power source available only about eight to ten hours a day.

The concept of tidal power is fairly old; waterwheels powered by tidal currents ground grain in eleventh-century England. Tidal power is tapped by building a dam with sluice gates across an estuary at a narrow opening to reduce construction costs. The sluice gates are opened to allow an incoming tide to increase the height of the water. When the tide turns, the sluice gates are closed, entrapping the water. As the tide goes out, the water level differential on either side of the dam widens until there is a sufficient head for water to pass through specially designed turbines to generate electricity.

A tidal dam must be located where there is a marked difference between high and low tides. One favored area proposed for building a tidal dam is the Bay of Fundy in eastern Canada, where the difference in water level between tides is over fifty feet, the highest in the world. Other areas with pronounced tides in the northern hemisphere are Cook Inlet in Alaska, the White Sea in Russia, and the coastline along eastern Russia, northern China, and Korea. In the southern hemisphere, potential sites are in Argentina, Chile, and western Australia. With electricity production limited to between eight and ten hours a day, a tidal dam has an effective output of only 35 percent or so of rated capacity and the timing of its maximum output may not correspond to the timing of peak demand. Moreover, a substantial investment is necessary to transmit the generated electricity from remote sites conducive to tidal dams to population centers.

The only major source of tidal energy in the world is the tidal dam at La Rance estuary in France, built in the 1960s, capable of producing 240 megawatts of electricity. It has a maximum tidal range of twenty-six feet, operates at 26 percent of rated capacity on average, requires low maintenance, and is in service 97 percent of the time. Three other such dams are far smaller; an 18-megawatt tidal dam at Annapolis Royal, Canada (Bay of Fundy), which serves the local area, a 3.2-megawatt dam in eastern China at Jiangxia, and a 0.4-megawatt dam in the White Sea at Kislaya, Russia. One proposal under consideration since the 1980s is to build a sixteen-kilometer (ten-mile) dam across the Severn estuary in the United Kingdom. It would have a maximum output of 8.6 gigawatts, employing 214 electricity-generating turbines, and would be capable of supplying about 5–6 percent of the United Kingdom's electricity demand.[34] Another under consideration since 1990 is a 48-megawatt tidal dam near Derby in northwestern Australia, but little progress has been made to date. South Korea is nearing the completion of what will be the world's largest tidal dam. An existing seawall between Sihung City and Daeboo Island created saltwater Lake Sihwa. Without an outlet, Lake Sihwa was becoming polluted. Constructing an outlet through the sea wall to flush the lake also allowed for the installation of turbines to take advantage of tidal flows. When in operation, the output of 254 MW will make it larger than the tidal dam at La Rance, France. South Korea has also embarked on another tidal dam at Inchon, near Seoul. The project, to be completed in 2014, will consist of a 4.8 mile barrier connecting four islands and containing turbines capable of generating 812 MW when the tide is flowing.[35]

A more effective way to harness tidal power is channeling tidal flow through a restricted waterway so that the tidal current powers turbines during incoming and outgoing tides. This "double flow" system provides electricity generation whenever the tides are running but not during a change in tides when the tidal current reverses. Though the double flow system has a higher effective output than the tidal dam, electricity generation is still not continuous and may not be timed to accommodate demand. One proposal, now defunct, was to build a tidal fence two and a half miles long (four kilometers) in the San Bernardino Strait in the Philippines between the islands of Samar and Dalupiri. The tidal fence would contain 274 turbines capable of generating 2,200 megawatts (2.2 gigawatts) at peak tidal flow. The Race Rocks Ecological Reserve off the coast of Vancouver Island has built a small power plant powered by tidal current in addition to a solar panel to supply most of its electricity demand by renewable sources. A larger installation has been built in Strangford Narrows, Northern Ireland, by Marine Current Turbines. When the tide is running, the tidal stream turbine powers a 1.2 megawatt generator sufficient to power 1,000 homes. Means to supply power when the tide is turning can be a battery charged when the tidal current is running. Another interesting solution is to use some of the generated electricity to compress air in a sealed cavern. During times when the tide is turning, or when the wind isn't blowing for wind turbines, the compressed air becomes a motive force to generate electricity.

The "double basin" method of tidal power provides a continuous supply of electricity because the water flows continually from a higher basin to a lower basin. Water in the upper basin is replenished during high tide and water accumulating in the lower basin is drained during low tide. Continuous power is possible by installing a turbine in a river as proposed for the Mississippi and the Niagara where power generation would not be interrupted by changing tides. Tidal or river currents with an optimal speed is 4.5 to 6.7 miles per hour (2 to 3 meters per second) turn a propeller that drives a generator whose output is transmitted to shore via underwater cables. In principle, this is similar to a wind turbine. The major difference is that water is 850 times denser than air, which allows a smaller propeller to generate electricity at a lower rate of rotation. (Fish learn to live with the rotating propellers whose speed is slow enough for them to escape contact.) A tidal turbine with thirty-four-foot-long blades has been built in Hammerfest, Norway, capable of generating 300 kilowatts of electricity when the tide is running to supply the local community of 35 homes. The European Marine Energy Centre describes tidal devices being built or proposed to capture tidal energy such as the horizontal axis turbine (one is installed in the East River of New York City), the vertical axis turbine, the oscillating hydrofoil, and other designs along with a list of over fifty companies in various stages of developing tidal power.[36] The largest water current electricity-generating scheme ever devised is the proposal to dam the Mediterranean at Gibraltar where the waterway is about ten miles wide. There are two currents at Gibraltar; a surface current of outgoing water and a deeper current of incoming water (submarines during the Second World War would "sneak" into the Mediterranean by drifting in this lower current).[37] The net flow of water is incoming as the Mediterranean and Black Seas evaporate more water than is entering via the Nile, Danube, Dnieper, and other rivers. Obviously gates would be necessary for the passage of ships. Enormous turbines would be installed in the dam powered by the incoming water current. The electricity-generating potential is enormous, but cost and obvious concerns over its environmental impact have stymied the project.

Waves are caused by wind and their enormous energy potential can be tapped by using hydraulic or mechanical means to translate the up-and-down motion to rotate a generator. Calm weather and severe storms affect the operation of these devices, but when in operation, electricity can be delivered to shore via underwater cables. While one may feel that this energy source is futuristic, tens of thousands of navigational buoys have long relied on wave motion to power their lights. The height of a column of water in a cylinder within the buoy changes with the up-and-down motion of the buoy, creating an air-pressure differential that drives a piston powering a generator to supply power for the lights, sound signals, and other navigational aids of the buoy. A battery is kept charged by the wave motion in case of calm weather. One wave-power system has been in operation since 1989, producing 75 kilowatts for a remote community at Islay in Scotland. Pelamis Wave Power builds sausage looking semisubmerged, articulated cylindrically shaped wave generators where internal hydraulic rams, driven by wave motion, pump high pressure oil through hydraulic motors to drive generators. Electricity is collected in a single underwater cable for transmission on shore. Load control maximizes output in quiet seas and limits output in dangerous weather. Precautions have to be taken to keep ships away from wave generators. Ocean Power Technologies produces a conventional looking buoy capable of converting wave energy to a mechanical stroking action that drives an electricity generator for servicing a shore community. Small generating buoys are deployed off the coast of New Jersey and Hawaii. A 1.4 megawatt installation is being built offshore northern Spain with a planned project for a 5 megawatt installation offshore U.K.[38] An entrepreneurial professor of electrical engineering has invented a simple "wave-energy converter" with only one moving part. The buoy consists of an outer cylinder with copper wires wound on its inside tethered to the bottom so that it remains stationary. Inside the cylinder is a float free to move with the wave motion. The magnet in the float generates a current as it moves up and down within the cylinder, and the generated electricity is transmitted to shore by an underwater power cable.[39]

The last method of extracting energy from the ocean is to take advantage of temperature differentials. The warm temperature of ocean surface water can be used to vaporize a working fluid, such as ammonia, which boils at a low temperature, to drive a turbine to generate electricity. The working fluid is cooled and condensed for recycling by deeper cold water. The warmed cold water must be pumped back into the ocean's depths to prevent cooling the surface. Ocean thermal systems are located in the tropics, where warm surface waters lie over deep cold waters. This provides the greatest temperature differential for operating a turbine; even so, the efficiency of heat transfer at these relatively small temperature differentials is only 5 percent, a technical challenge that requires building and operating a heat exchanger large enough to produce a significant amount of electricity. Demonstration plants have been built, including one in Hawaii that produced up to 250 kilowatts of electricity for a number of years. However, technical problems associated with ocean thermal energy still pose a significant barrier to developing this source of energy on a commercial scale.

One idea is to have "grazing plants" located far from shore where temperature differentials are the greatest. This precludes having an underwater cable connecting the grazing plant to the shore. The generated electricity would produce hydrogen by electrolyzing water. Hydrogen then becomes a stored form of electricity that can be shipped from the grazing plants in specially designed vessels to shore-based terminals for further distribution as an energy source for fuel cells in automobiles and homes.

NOTES

1. Environment and Development (also known as the Brundtland Commission), 1987.

2. "Energy Use in Cities" Chapter 8, *Global Energy Outlook* published by the IEA, Paris, 2008; and "Emission Control Measures in Shanghai, China" published by Institute for Global Environmental Strategies Web site www.iges.or.jp/APEIS/RISPO/inventory/db/pdf/0031.pdf.

3. "Energy Use in Cities" Chapter 8, *Global Energy Outlook* published by the IEA, Paris, 2008; and "Emission Control Measures in Shanghai, China" published by Institute for Global Environmental Strategies Web site www.iges.or.jp/APEIS/RISPO/inventory/db/pdf/0031.pdf.

4. Anup Shah, "Sustainable Development Introduction" Web site www.globalissues.org/article/408/sustainable-development-introduction 2005.

5. India Climate Solutions Web site www.indiaclimatesolutions.com/pump-sets-irrigation-and-human-power.

6. Darrell M. Dodge, *Illustrated History of Wind Power Development,* Web site www.telosnet.com/wind/index.html. Unless otherwise indicated, this is the chief source of information on the development of windmills and wind turbines.

7. Vaclav Smil, *Energy in World History* (Boulder, CO: Westview Press, 1994).

8. As a child I lived on an estate dairy farm on Long Island that had a large wooden windmill, perched on top of a tall stucco and brick tower, that was used for pumping and storing water; but by then, the windmill was no longer operable and the tower had been converted to a silo for corn.

9. Web site energy.sourceguides.com/businesses/byP/wRP/lwindturbine/byB/mfg/byN/byName.shtml contains a full listing of wind turbine manufacturers.

10. Figures 9.1, 9.2, and 9.3 data are from Global Wind Energy Council's Web site www.gwec.net, along with the American and the European Wind Energy Associations Web sites www.awea.org and www.ewea.org, respectively.

11. Keith Bradsher, "Drawing Critics, China Seeks to Dominate in Renewable Energy," *New York Times* (July 14, 2009) p. B1.

12. General Electric Web site www.gepower.com/prod_serv/products/wind_turbines/en/15mw/index.htm.

13. Terra Moya Aqua (TMA) Web site www.tmawind.com.

14. *Outlook 2005 for Wind Power,* American Wind Energy Association Web site www.awea.org.

15. For example, the Australian joint venture utility company ActewAGL offers the GreenChoice Program, Web site www.actewagl.com.au/environment/default.aspx.

16. Solar Energy Technologies Program of the U.S. Department of Energy, Energy Efficiency and Renewable Energy Web site www.eere.energy.gov/solar/solar_time_7bc-1200ad.html.

17. Solar Energy History Web site www.facts-about-solar-energy.com/solar-energy-history.html; and Solar Panels Plus Web site www.solarpanelsplus.com/solar-energy-history; and Solar Energy History Web site www.solarevents.com/articles/solar-energy/solar-energy-history; and Ausra "A History of Solar Power" Web site www.ausra.com/history/index.html.

18. United Nations Development Program (UNDP), "World Energy Assessment: Overview 2004 Update," New York, 2004.

19. National Renewable Energy Laboratory's Web site www.nrel.gov.

20. Energy Efficiency and Renewable Energy Solar Technologies Program Web site www.eere.energy.gov/solar/csp.html.

21. Enviromission Company Web site www.enviromission.com.au.

22. Data for Tables 9.1 and 9.2 obtained from ECO Worldly Web site ecoworldly.com.

23. Solar Energy Technologies Program of the U.S. Department of Energy Efficiency and Renewable Energy Web site www.eere.energy.gov/solar/pv_cell_light.html.

24. PV Power Resource Web site www.pvpower.com.

25. For more information on BP Solar installations in remote locations, see Web site www.bp.com/genericarticle.do?categoryId=3050422&contentId=7028813.

26. International Energy Agency Photovoltaic Power Systems Program 2007 Report, Web site www.iea-pvps.org.

27. Arizona Power Service solar program is described on Web site www.aps.com/main/green/choice/choice_82.html.

28. "Solar Grand Plan," *Scientific American* (January 2008), p. 65–73; also available at Web site www.scientificamerican.com/article.cfm?id=a-solar-grand-plan.

29. Geothermal Education Office Web site geothermal.marin.org.

30. Geothermal Resources Council Web site geothermal.org.

31. Geodynamics Ltd. Web site www.geodynamics. com.au.

32. "Swiss Geothermal Project Causes Earthquakes" published online by *Scitizen* (September 12, 2007), Web site http://www.scitizen.com/.

33. Wendell A. Duffield and John H. Sass, *Geothermal Energy–Clean Power from the Earth's Heat,* Circular 1249 (Washington, DC: U.S. Geological Survey, U.S. Department of the Interior, 2003).

34. For the current status of this project, see Web site www.reuk.co.uk/Severn-Barrage-Tidal-Power.htm.

35. Environmental & Energy Research at the Washington University in St. Louis, Web site www.eer.wustl.edu/McDonnellMayWorkshop/Presentation_files/Saturday/Saturday/Park.pdf.

36. European Marine Energy Centre (EMEC) Web site www.emec.org.uk.

37. The 1981 movie *Das Boot* shows a submarine taking advantage of this current.

38.Palamis Wave Power Web site www.pelamiswave.com; Ocean Power Technologies Web site www.oceanpowertechnologies.com. See also European Marine Energy Centre for description of wave generating devices and companies involved with this technology Web site www.emec.ort.uk.

39. "Catching a Wave" by Elizabeth Rusch, *Smithsonian* (July 2009), vol. 40, no 4, p. 66.

10

LOOKING TOWARD THE FUTURE

This chapter deals with the hydrogen economy, climate change, the impact of fossil fuels on the environment, legislative acts to deal with air pollution, and energy efficiency and conservation.

THE HYDROGEN ECONOMY

Hydrogen is the most abundant element in the universe, making up 75 percent of its mass and 90 percent of its molecules. Hydrogen, when burned as a fuel, emits only water and heat, the cleanest source of energy by far. Though plentiful in the universe, there is no free hydrogen here on Earth. While a portion is locked away in hydrocarbons and other chemicals, most of what there is has already been burned and its product of combustion is all around and in us: water.

Curiously, human progress in energy has been marked with decarbonizing fuel sources. For most of history, humans burned wood, which has the highest ratio of carbon to hydrogen atoms, about ten carbon atoms per hydrogen atom, in comparison to fossil fuels. This means that burning wood emits more carbon dioxide than burning fossil fuels for an equivalent release of energy. Coal, the fossil fuel that sparked the Industrial Revolution, has about one or two carbon atoms per hydrogen atom, which means it emits less carbon dioxide than wood. Next is oil, with one half of a carbon atom per hydrogen atom (or one carbon atom for every two hydrogen atoms), and natural gas is last, with one-quarter of a carbon atom per hydrogen atom (or one carbon atom for every four hydrogen atoms). Thus, as people have learned to use new fuels, each one was a step down in carbon dioxide emissions for an equivalent release of energy. The ultimate step is hydrogen, which has no carbon atoms and, therefore, no carbon dioxide emissions, no emissions of carbon monoxide, sulfur, nitrous oxides and other progenitor chemicals that create smog, and no metallic emissions (mercury, arsenic); hydrogen produces only plain water and heat.

Henry Cavendish discovered "inflammable air" in 1766 and Antoine Lavoisier renamed it hydrogen. Hydrogen is colorless, odorless, has no taste, and burns with a pale blue flame virtually invisible in daylight. In the 1870s, Jules Verne thought that water would be the fuel of the future. In 1923, John Haldane predicted that future energy would be in the form of liquid hydrogen. Rows of windmills would generate electricity to produce hydrogen by the electrolysis of water. Hydrogen gas would then be liquefied and stored in vacuum-jacketed underground reservoirs until needed to generate electricity when recombined with oxygen. Although his idea was ridiculed at the time, Haldane's prediction is essentially where we are headed today.[1]

The fuel for the engines on German-made Zeppelin dirigibles that carried passengers between European cities and across the Atlantic Ocean to the United States varied from diesel fuel to a mixture of benzene and gasoline, augmented by excess hydrogen blow-off as a booster fuel. The crash of the *Hindenburg* in 1937 ended the days of dirigibles filled with hydrogen, which was replaced with