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Energy Transitions:
A Curious History

By Richard Rhodes

Center for International Security and Cooperation

Stanford University

September 19, 2007

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Richard Rhodes
Rhodes.Today@comcast.net
www.RichardRhodes.com

Energy Transitions: A Curious History

Talk delivered at The Security Implications of Increased Global Reliance on Nuclear Power Conference *Dinner, Wednesday, 19 September 2007, Stanford University, Stanford CA.*

Since you're dealing with the transition ongoing in the world to nuclear energy, I thought it might be comforting to hear a little about the problems of earlier energy transitions—from wood to coal and from coal to oil as well as natural gas and nuclear power. Energy transitions take time, writes Arnulf Grübler.[1] "Hardly any innovation diffuses into a vacuum," he says. "Along its growth trajectory, an innovation interacts with existing techniques…and changes its technological, economic, and social characteristics.…Decades are required for the diffusion of significant innovations, and even longer time spans are needed to develop infrastructures.…"[2] The diffusion process is a process of learning, and humans learn slowly.

The historic substitution of coal for wood was fundamental to the Industrial Revolution. Coal had been known and used for three thousand years, but only marginally. Its social characteristics were wrong for a society organized around burning wood: compared to wood, it was dirty; it stank; it required different skills and technologies to collect and distribute; and its smoke was more toxic. In Tudor England, where wood smoke was believed to harden the house timbers and disinfect the air, chimneys were uncommon; the smoke from fires was simply allowed to drift out the windows.[3] But sixteenth-century London suffered from a problem familiar to urban conurbations in developing countries today: As the city grew, a farther and farther area around it became deforested, and as transportation distances increased, wood became more expensive. The poor had to switch to coal; the rich resisted. "Even in late Elizabethan times," writes a historian, "…it was evident that the nobility still objected strongly to the use of the fuel. Well-bred ladies would not even enter rooms where coal had been burnt, let alone eat meat that had been roasted over a…coal fire, and the Renaissance Englishman was not keen to accept beer tainted with the odor of coal smoke."[4]

Brewing, however, was one London industry that turned to coal as wood and charcoal became scarce; so did dyers, lime burners and salt- and soap-boilers. The nobility began to accept the transition when Queen Elizabeth died in 1603 and the throne passed to James I, who had been James VI of Scotland. Scottish nobles had faced wood shortages earlier than the English and had access to less sulfurous coal, "so the new king used the fuel in his household when he moved to London."[5] Coal thus became fashionable, and none too soon. By 1700, coal production in England and Wales had reached three million tons per year—half a ton per capita.[6] By 1800, production had tripled to nine million tons per year.[7]

There were two fundamental technological challenges to increasing coal production. One was that deepening coal mines penetrated the water table and flooded the mines: the water needed to be pumped away. Steam engines were developed first of all for pumping out coal mines. "Three quarters of the patents issued in England between 1561 and 1668 were connected with the coal industry…and…a seventh were concerned with the drainage problem."[8] And since the steam engines burned coal, the new energy source was bootstrapping itself.

The other fundamental challenge of using coal was transportation. Wood, which grew dispersed across the landscape, could be transported efficiently in small batches in carts and on river boats. Coal was not areal, like wood, but punctiform—that is, it came out of a hole in the ground—and efficiency required its transportation in bulk. At first it was delivered by sea from mines near ports. There were 400 smaller colliers—boats carrying coal—working between Newcastle and London in 1600; by 1700 that number had increased to 1,400, and the boats were larger. By 1700 "about half of the total British merchant fleet by tonnage was engaged in the coal trade."[9] But as use grew and mines were opened inland, coal drove the development of canals.

Then the technologies developing to meet the challenges of coal production combined. The first railways, horse-drawn, had connected pitheads with coal wharves to move coal onto colliers for transport by sea. The steam engine, mounted on wheels that ran on rails, offered faster and more powerful transportation. "Railways were peculiarly a mining development (even down to the track gauge)," an English historian explains, "and were created to overcome the problems posed by large-scale punctiform mineral production, initially as feeders to waterways, but later as an independent network. Like canals, they also, of course, proved in time of great benefit to other forms of production and made easier the movement of the vegetable and animal raw materials. Moreover, they developed a great passenger traffic."[10]

Energy transitions transform societies. Let me quote two somewhat opposing views of the coal transformation, to demonstrate how complex such transformations are. Both the writers are economists. The first view:

> The abundance and variety of [the Industrial Revolution's] innovations almost defy compilation, but they may be subsumed under three principles: the substitution of machines…for human skill and effort; the substitution of inanimate for animate sources of power, in particular the introduction of engines for converting heat into work, thereby opening to man a new and almost unlimited supply of energy; [and] the use of new and far more abundant raw materials, in particular the substitution of mineral for vegetable or animal substances.
>
> These improvements constitute the Industrial Revolution. They yielded an unprecedented increase in man's productivity and, with it, a substantial rise in income per head. Moreover, this rapid growth was self-sustaining. Where previously, an amelioration of the conditions of existence…had always been followed by a rise in population that eventually consumed the gains achieved, now, for the first time in history, both the economy and knowledge were growing fast enough to generate a continuing flow of investment and technological innovation, a flow that lifted beyond visible limits the ceiling of Malthus's positive checks. The Industrial Revolution thereby opened a new

> age of promise. It also transformed the balance of political power, within nations, between nations, and between civilizations; revolutionized the social order; and as much changed man's way of thinking as his way of doing.[11]

The second view, commenting on the first:

> This account has the merit of symmetry, but the notion of substitution is problematic, since in many cases there are no real equivalents to compare. The fireman raising steam in an engine cab, or the boilermaker flanging plates in a furnace, were engaged in wholly new occupations which had no real analogy in previous times.…If one looks at technology from the point of view of labor rather than that of capital, it is a cruel caricature to represent machinery as dispensing with toil. High-pressure engines had their counterpart in high-pressure work, endless-chain mechanisms in non-stop jobs. And quite apart from the demands which machinery itself imposed there was a huge army of labor engaged in supplying it with raw materials, from the slave laborers on the cotton plantations of the United States to the tinners and copper miners of Cornwall. The industrial revolution, far from abridging human labor, created a whole new world of labor-intensive jobs: railway navvying is a prime example, but one could consider too the puddlers and shinglers in the rolling mills, turning pig-iron into bars, the alkali workers stirring vats of caustic soda, and a whole spectrum of occupations in what the Factory legislation of the 1890s was belatedly to recognize as "dangerous"

> trades. Working pace was transformed in old industries as well as new, with slow and cumbersome methods of production giving way, under the pressure of competition, to overwork and sweating.[12]

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The second great energy transition originated in the United States, and like the transition to coal, it began with a preadaptation. Coal's preadaptation was its substitution for domestic wood burning, which then led to its application to steam power in mining, transportation and manufacturing. Oil was first used as a substitute for whale oil for illumination in the form of kerosene, another example of substituting mineral for animal or vegetable raw materials. As a pamphleteer wrote in 1860, a year after Uncle Billy Smith struck oil at Oil Creek in Titusville, Pennsylvania, "Rock oil emits a dainty light, the brightest and yet the cheapest in the world; a light fit for Kings and Royalists and not unsuitable for Republicans and Democrats."[13] Kerosene remained the most important oil product for decades, with smaller markets developing for naphtha; gasoline, which was used as a solvent or gasified for illumination; fuel oil; lubricants; petroleum jelly and paraffin wax.

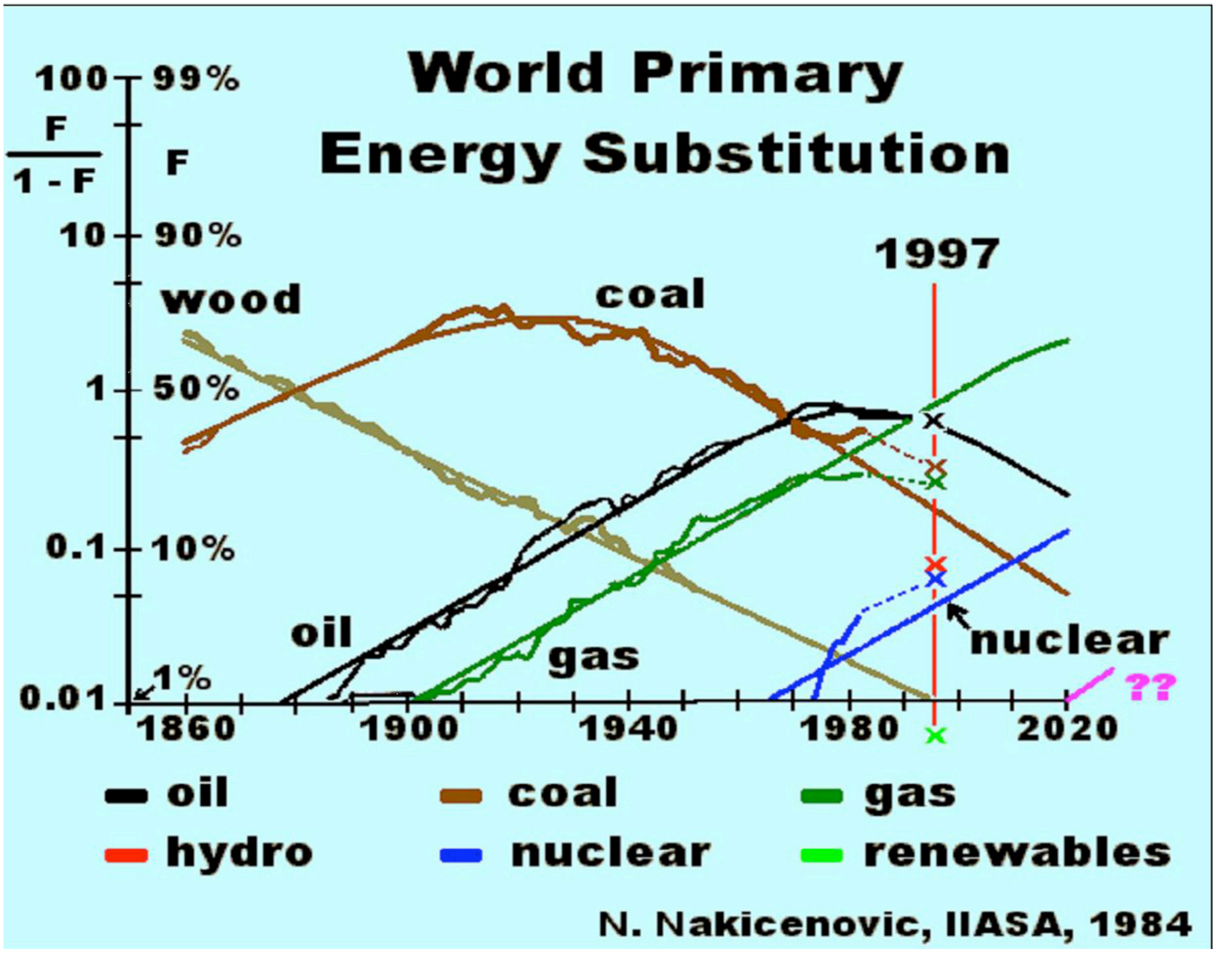
At the beginning of the twentieth century, coal still accounted for more than 93 percent of all mineral fuels consumed in the United States, and electric light was rapidly displacing the kerosene lantern in urban America, with 18 million light bulbs in use by 1902. Oil might have declined, because it was much more expensive per unit of energy than coal, but because it is a liquid it is also much cheaper to transport. Even as late as 1955, the cost per mile of transporting a ton of liquid fuel energy by tanker or pipeline was less than 15 percent of the cost of transporting an equal amount of coal energy by train. Large oil fields were discovered in Texas and California early in the century. Railroads in the West and Southwest almost immediately converted to oil burning, because local oil was cheaper than distant coal when transport was figured in. Total energy consumption in the U.S. more than doubled between 1900 and 1920, making room for oil to expand its market share without directly challenging the coal industry. Steamships offered another major market. The U.S. Navy converted to fuel oil before the First World War, a conversion which functioned as an endorsement for private shippers. And as with coal, a significant bootstrapping market was the oil industry itself, which used oil both to fuel its oil tankers and "to provide the intense heat needed for petroleum refining….An estimated [five to ten] percent of all oil produced in this period was burned in the refineries."[14]

The introduction of the automobile secured oil's market share. "Animal feed," writes Nebojsa Nakicenovic, "reached its highest market share in the 1880s, indicating that draft animals provided the major form of local transportation and locomotive power in agriculture….Horse[-drawn] carriages and wagons were the only form of local transportation in rural areas and basically the only freight transportation mode in cities. In addition, they moved goods and people to and from railroads and harbors."[15] Henry Ford's original intention was to develop a farm tractor. "It was not difficult for me to build a steam wagon or tractor," he wrote in his autobiography. "In the building of it came the idea that perhaps it might be made for road use….The obvious thing to do was to design and build a steam engine that would be light enough to run an ordinary wagon or to pull a plow. I thought it most important first to develop the tractor. To lift farm drudgery off flesh and blood and lay it on steel and motors has been my most constant ambition. It was circumstances that took me first into the actual manufacture of motor cars. I found eventually that people were more interested in something that would travel on the road than in something that would do the work on the farms."[16] By manufacturing motor cars, Ford and his competitors relieved farm labor by reducing the demand for animal feed: in Great Britain, for example, the annual feed bill for town horses in the 1890s approached 100 percent of the annual value of all crops sold off British farms.[17]

In Nakecenovic's analysis, the automobile first substituted for and displaced the horse-drawn carriage, largely because it increased the radius of local transportation, allowing "entrepreneurs to expand their circles of customers and [offering] a more flexible mode of leisure and business transport."[18] Only after that process was completed, in the 1920s, "did it emerge as an important transportation mode in competition with the railroad for long-distance movement of people and goods."[19] Just at that time, natural gas began penetrating major industrial markets such as iron and steel, cement, textiles, food, paper and pulp which burned coal or had recently switched to fuel oil, "freeing petroleum to meet the rising demand for gasoline."[20]

Preadaptations that prepared the way for the automobile included the availability of gasoline as a refinery byproduct and the surfacing of roads for horse-drawn carriages. Eight percent of all U.S. roads were already surfaced by

1905, when there were fewer than 80,000 automobiles in use but more than three million non-farm horses and mules.[21] The diesel engine was originally conceived as a combustion engine for powdered coal, but the resulting ash ground and fouled its cylinders and pistons; diesel fuel, another refinery byproduct, made it practical.[22]



World Primary Energy Substitution

N. Nakicenovic, IIASA, 1984

By 1950, fuel wood comprised only 3.3 percent of aggregate U.S. energy consumption and natural gas 17 percent, but coal and oil closely matched each other with somewhat more than 36 percent each.[23] Oil's market share peaked in 1968 at only 43 percent, much lower than coal's earlier peak of 70 percent. Natural gas had emerged to compete with oil only 20 years after oil's emergence. The gap had been much wider between coal and oil—about 150 years. Today both coal and oil are declining as fractions of total world energy, although oil demand is at a maximum. "The oil industry still has most of its future in front of it," Cesare Marchetti predicts, with a mean loss of production across its decline of only 1.6 percent per year.[24] But the longer future belongs to natural gas, which Marchetti expects to reach a maximum market share of 70 percent—"like coal"—around the year 2040.[25] Natural gas had time to gain a large market share because its next competitor, nuclear power, emerged a long seven decades later. Seventy percent market share for gas will be a huge share of a huge market, and if you wonder where all the gas will come from, the answer seems to be that the search for hydrocarbons is controlled much more by geopolitics than by the probability of discovery.[26]

The preadaptation that prepared the emergence of nuclear power has continued to haunt it.[27] In the United States, the Soviet Union, Great Britain, France and China, nuclear reactors were developed first of all to breed plutonium for nuclear weapons. Power reactors were delayed in the United States in the years immediately after the Second World War because everyone involved in the new atomic energy enterprise believed that high-quality uranium ore was rare in the world, too rare to be diverted from weapons production. Early in the 1950s the U.S. Atomic Energy Commission even considered extracting uranium from coal ash, where burning concentrates coal's natural complement of uranium ore. (The Chinese are again considering the idea today.) Well into the 1950s, almost the entire U.S. production of uranium and plutonium was dedicated to nuclear weapons. Finally the federal government offered bonuses to uranium prospectors for high-quality finds and the prospectors, reprising the California Gold Rush, unearthed the extensive uranium resources of the Colorado Plateau.

Another delay arose from concerns for secrecy. The Atomic Energy Act of 1946 made atomic energy an absolute monopoly of the federal government. All discoveries were to be considered "born" secret—treated as secret until formally declassified—and the penalty for divulging atomic secrets was life imprisonment or death. All uranium and plutonium became the property of the government, as beached whales once became the property of kings. No one could build or operate a nuclear reactor except under government contract, nor could one be privately owned. All these restrictions and mindsets had be revised before utilities could own or build nuclear power stations.

It's clear in hindsight that the careful evolutionary development of nuclear power in the United States, including the types of reactors developed and the nurturing of a solid political constituency, were casualties of the Cold War. Early in the 1950s, the Soviet Union announced a power reactor program, and by then the British were developing a power reactor fueled with natural uranium that countries without enrichment facilities might want to buy. In both cases Congress feared the U.S. might be left behind. It amended the Atomic Energy Act in 1954 to allow private industry to own and operate reactors, and government-subsidized construction began on a 60,000-kilowatt demonstration plant at Shippingport, Pennsylvania, the same year. The reactor design derived from a Westinghouse Large Ship Reactor, a pressurized-water reactor developed for aircraft carriers, but to limit proliferation, Hyman Rickover made the bold decision to switch from uranium metal fuel to uranium oxide.

The PWR configuration met the needs of the U.S. Navy, but it was less than ideal for commercial power. Water was a less efficient but familiar coolant. Uranium oxide, which became the standard light-water reactor fuel, is less dense than uranium metal and conducts heat much less efficiently. To make their compromise reactor designs competitive in a field dominated by relatively cheap fossil fuels, reactor manufacturers pushed design limits, maximizing temperatures, pressures and power densities. Tighter design limits led to more frequent shutdowns and increased the risk of breakdowns, which in turn required more complex safety systems.

More crucially, manufacturers began pursuing economies of scale by selling larger and larger reactors, without fully addressing the changing cost and safety issues such reactors raised. “The largest commercial facility operating in 1963,” two policy analysts write, “had a capacity of 200 megawatts; only four years later, utilities were ordering reactors of 1,200 megawatts.”[28] But the safety arrangements that government regulators judged sufficient at 200 megawatts they no longer judged sufficient at 1,000 megawatts. So they began requiring further add-on safety systems, escalating engineering and construction costs. Construction time increased from seven years in 1971 to 12 years in 1980, roughly doubling the cost of the plants and raising the cost of the resulting electricity. Nuclear Regulatory Commissioner Peter Bradford would write later that “an entire generation of large plants was designed and built with no relevant operating experience, almost as if the airline industry had gone from Piper Cubs to jumbo jets in about fifteen years.”[29] Because of the scale-up in size and the correspondingly larger inventory of fuel, “engineered safety” replaced “defense in depth” as a design philosophy, and it became impossible to demonstrate that large U.S. power reactors were acceptably safe. Nor was a safety culture developed and maintained among the operating teams at private utilities lacking experience in nuclear power operations.

It was these problems, and not antinuclear activism, that led to the cancellation of orders and the halt in construction that followed the Arab oil embargo that began in late 1973. Orders for some 100 U. S. nuclear power plants were cancelled; but orders for 82 coal power plants were also cancelled—nearly 200,000 megawatts cancelled or deferred in all—because the oil embargo stimulated dramatic improvements in energy conservation in the U.S. that stalled a longstanding trend of increasing demand. “Who…would have predicted,” Al Weinberg would write, “that the total amount of energy used in 1986 would be only 74 quads, the same as in 1973?”[30] Today, with demand once again increasing, U.S. nuclear power is thriving: existing plants are being relicensed to extend their operating life another 20 years; plants left unfinished will probably be finished and licensed; and new reactor construction utilizing newer, safer and more efficient designs is pending.

Fusion, if it can be made practical, fits in well with these historic trends in energy development. Like nuclear power, it also continues another trend that Grübler and Nakicenovic have identified historically, a trend toward increasing decarbonization, meaning a decrease in the amount of carbon or CO_2 emitted per unit of primary energy consumed.[31] The carbon intensity of primary energy use today is some 30 to 40 percent lower than in the mid-nineteenth century. The long-term trend toward decarbonization—it averages out to about 0.3% per year—will not be sufficient by itself to limit or reverse the greenhouse buildup, but at least it is moving in the right direction. Solar, wind and biomass also fit this trend toward decarbonization, but unlike those energy systems, fusion is punctiform rather than areal, and the trend has been away from areal energy sources for more than two hundred years. Renewables are also lower-grade energy sources than fusion, another trend in its favor.

But in truth, we will need every energy source we can find or devise. Coal as it is presently used will no doubt continue to decline in world market share, but it may find renewal in a new form, as a liquid fuel supplementing petroleum. That would extend coal's contribution for another hundred years.

The fundamental human project is the alleviation of suffering through the progressive materialization of the world. In the longest run, into the 22nd century, nuclear, solar and fusion electricity and hydrogen fuel promise health, a cleaner environment, an adequate standard of living, a life expectancy of at least 70 years and consequently a minimum of war and civil conflict for a sustainable world population of even ten billion souls. If that sounds like the fulfillment of the fundamental human project—well, let's hope.

Thank you.

Notes

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[1] IIASA (1981), p. 100.
[2] Grübler (1991), p. 159, p. 163.
[3] Brimblecombe (1987), p. 35.
[4] Brimblecombe (1987), p. 30.
[5] Brimblecombe (1987), p. 30.
[6] Wrigley (1994), p. 94.
[7] Wrigley (1994), p. 94.
[8] Wrigley (1994), p. 11.
[9] Wrigley (1994), p. 6.
[10] Wrigley (1994), p. 8.
[11] Landes (1994), p. 108.
[12] Samuel (1994), p. 198.
[13] Quoted in Yergin (1991), p. 28.
[14] Pratt (1981), p. 17.
[15] Nakicenovic (1986), p. 313.
[16] Quoted in Rhodes (1999), p. 35.
[17] Thompson (1994), pp. 282-283.
[18] Nakicenovic (1986), p. 316.
[19] Nakicenovic (1986), pp. 316-317.
[20] Pratt (1981), p. 18.
[21] Pratt (1981), p. 317.
[22] Cottrell (1955), p. 107.
[23] Pratt (1981), Table 1, p. 10.
[24] Marchetti (1987a), p. 160.
[25] Marchetti (1987b), p. 390.
[26] Marchetti (1987a), p. 166.
[27] My discussion of the history of nuclear power is drawn from Rhodes (1993).
[28] Joseph Morone and Edward Woodhouse, quoted in Rhodes (1993), p. 44.
[29] Quoted in Rhodes (1993), p. 45.
[30] Weinberg (1990), pp. 212-213.
[31] Cf. Grübler and Nakicenovic (1996); Nakicenovic (1996).