

Chapter 1

The Technology of the “Grid”: Expansion and Extension in the 1940s and 1950s

Prior to World War II, the structure of the electric power industry had tended toward the centralization of generation in plants of increasing scale, the use of higher and higher transmission voltages, and the interconnection of large geographical areas into single networks.⁷ Although local variations of this technology existed, for purposes of discussion this can be called the “interconnected grid” model of electrical distribution. By 1945, these grids were highly integrated both technically and organizationally. Most power providers were either giant corporations or government-run administrations, depending on the country and form of government. In some countries ownership was mixed, but the organizations engaged in power production were remarkably similar in both for-profit and “nationalized,” government-owned systems. Almost all tended to treat electric power supply as a “natural monopoly” best undertaken through the rationalization and standardization of electric technologies. The effort to integrate the power supply into a single grid encouraged the development of certain kinds of technologies that worked best in large-scale systems.

From the 1920s to the 1950s, the huge enterprises that controlled power generation and distribution were repeatedly held up as models for a more efficiently run society. The differences between for-profit corporations and public institutions tended to blur, leading even the anti-socialist U.S. government to experiment with government ownership of the means of production. The Tennessee Valley Authority, created in the 1930s, serves as an outstanding example. The dire energy shortages created by World War II accelerated the process, and by 1945 “Federal power” accounted for over 12 percent of the total U.S. capacity. Though the U.S. government’s direct role in power

production would later decline, its presence presaged the heavy Federal sponsorship of research and development for nuclear power and other new electric power technologies.⁸

1. EXPANSION OF INTERCONNECTION

Whether public or private, the established power providers in industrialized nations had similar ideas about expansion based on the incremental extension of existing facilities rather than dramatic technical change. By 1945, most American cities already had central station power, manufacturing facilities had long since adopted it, and the new suburbs always included provisions for electric service. While some Americans, primarily farmers, were still without central station power, the Rural Electrification Administration continued its push for farm electrification well into the 1950s. Many existing users of electricity demanded more in the postwar period, so most utilities were having trouble building power plants and lines fast enough to keep up with demand. The average household use of electricity in 1950, for example, was more than three times what it had been in 1935.

As demand grew at a rate of 7 to 8 percent per year in the 1950s and 1960s, American power utilities operated near capacity during peak loads and were building new capacity as quickly as possible.⁹ The industry's response was to continue what it had been doing, but at a faster rate; that is, to build new, larger power plants and integrate them into networks or grids of ever-increasing size and complexity. One symbol of the trend toward increasing scale in the American power industry was indicated by the growing size of the steam turbogenerators supplied by equipment manufacturers, such as the 1000 MW "Big Allis" turbogenerator built by Allis-Chalmers in 1965 for the Consolidated Edison company of New York. Generator capacities peaked in the mid-1970s, with a giant 1500 MW unit located in Germany being the largest built to date.¹⁰

These large generators served grids that had grown to national or international scale. In the United States, the older industrial areas of the northeastern part of the country, served by a number of utility companies, interlocked their grids in the 1950s and 1960s. The most famous example was the Pennsylvania-New Jersey-Maryland Interconnection. Having its origins in the more limited Pennsylvania-New Jersey Interconnection of 1927, this system expanded in 1956 and

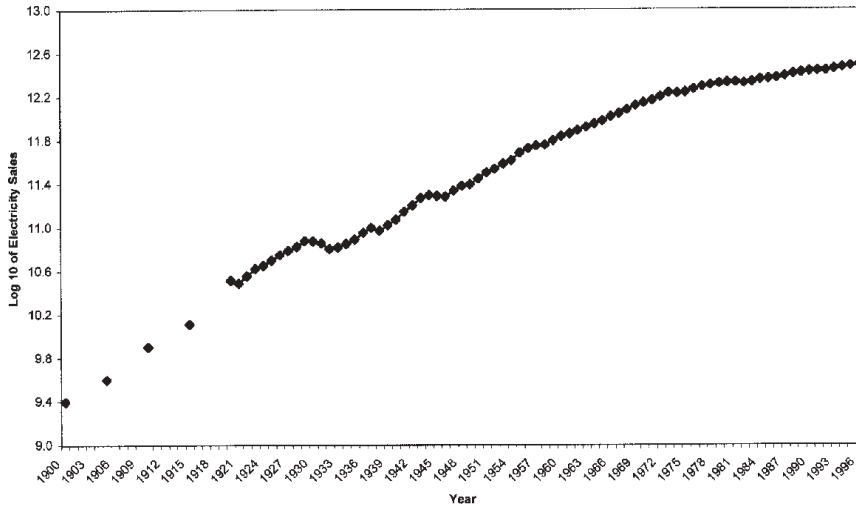


Figure 1. Sales of Electricity to Ultimate Consumers, 1900-1996.. Courtesy of Richard F. Hirsh.

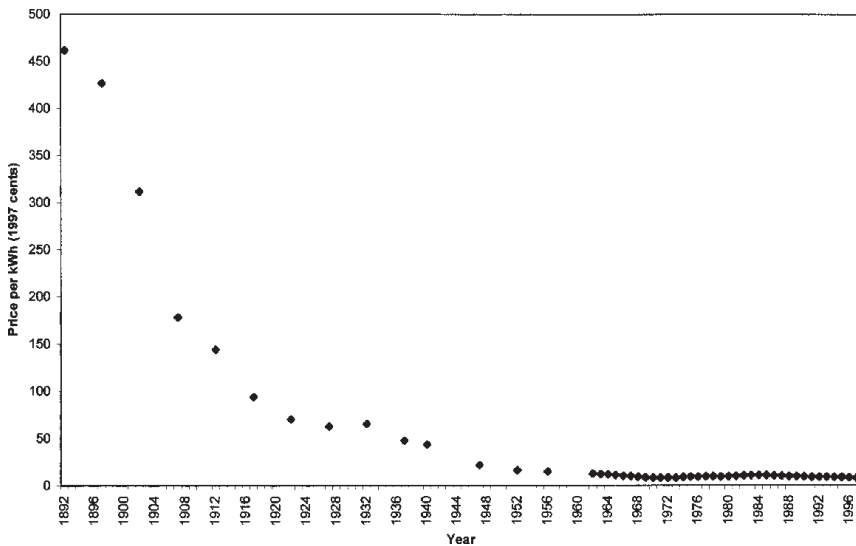


Figure 2. Average Residential Price of Electricity 1892 to 1997. Courtesy of Richard F. Hirsh.

eventually supplied about 19,000 MW to over twenty million people spread over 80,000 square kilometers. American systems also made links to new generating sites in Canada, a country with enormous water resources suitable for hydroelectric generation. For example, Canada's Churchill Falls hydroelectric complex in Labrador, which

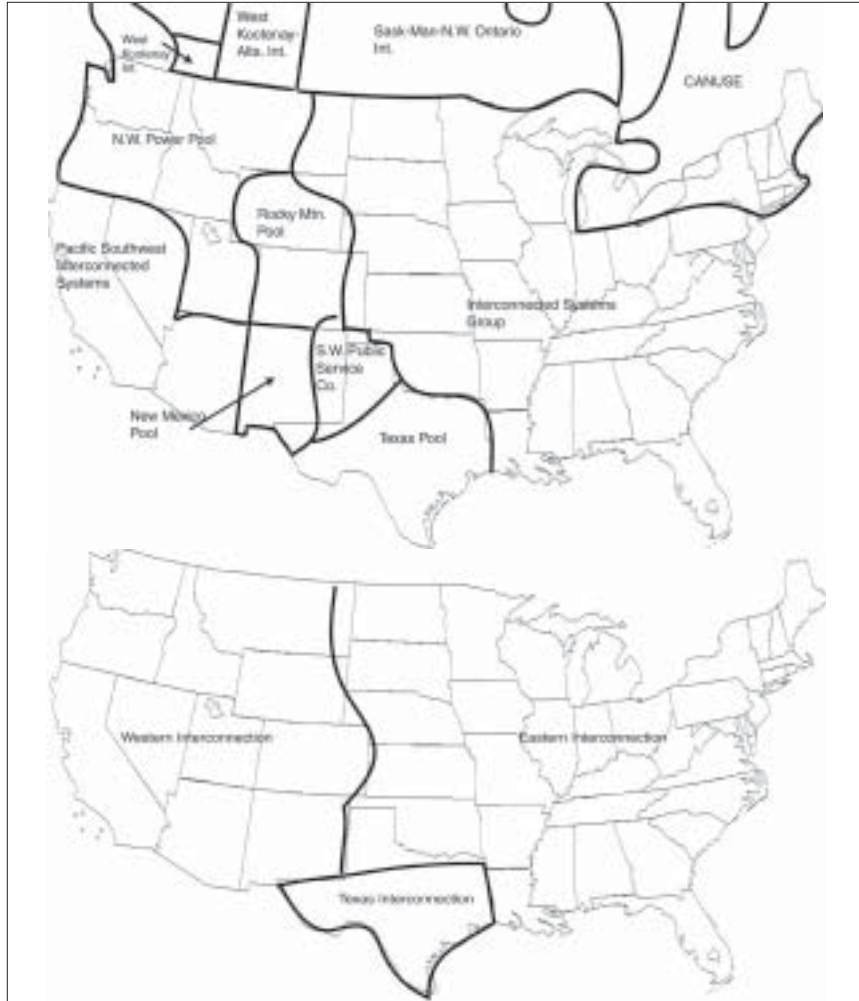


Figure 3. Postwar integration of large "power pools" in the United States. Upper illustration is from 1964 showing the approximate boundaries of eight regional grids and an already massive Interconnected Systems Group. Lower illustration is from 1984, showing only three remaining pools.

began operating in 1965, ultimately had a capacity of 5225 MW, delivered over 735 kV lines to the Montreal area, and eventually also delivered to load centers elsewhere in Canada and the U.S.¹¹

The new regional networks operated in isolation for only a few more years before engineers began to make region-to-region links. The Pennsylvania-New Jersey-Maryland Interconnection, for example, operated independently until 1962, with only a few

low-capacity emergency tie-lines to other systems. Yet the inexorable drive to engineer larger systems soon resulted in further integration, and the first high current links to other systems were built.¹²

Similarly, by the 1960s, the vast middle section of the U.S. was integrated into a single inter-regional grid. Power supply in this region was dominated by the giant utility company American Electric Power. AEP constructed some of the longest, highest-voltage transmission systems in the postwar period, most notably its 765 kV system, begun in 1967. This backbone transmission line traversed parts of six states and took about a decade to complete.¹³ It was also during this period that approximately 100 utility companies in thirty-two states created an Interconnected Systems Group (ISG) to cooperate on further integration. The ISG plan was to create what was in effect a single, giant network covering the vast area of the southeast and central portions of the United States.¹⁴

Much network development also occurred in the Western United States, where new sources of hydroelectric power on the Columbia River and elsewhere in the Pacific Northwest were joined with load centers farther south. A proposed Pacific Northwest-Southwest Intertie in 1964 required authorization from the governments of the United States and Canada, since it required considerable cooperation from each country. The trunk of the new system was composed of two 500 kV ac lines and two 750 kV dc lines running from the John Day and Dalles Dams into the Los Angeles area. The project, costing more than \$700 million, was paid for mainly by the Federal government and private utilities, with the City of Los Angeles contributing approximately \$70 million.¹⁵

Around the world, similar instances of power grid integration have taken place continuously since 1945. The Soviet Union, for example, had over 15,000 km of 330 kV or higher transmission lines in place by 1967, and operated 10 regional grids. Many European nations, often for political reasons, had only limited power links to neighboring countries, though with the recent advent of the European Union that situation has changed.¹⁶

2. POWER SHORTAGES AND THE "RELIABILITY" CRISIS

An unanticipated result of the growing scale of regional power networks was the increased possibility of massive outages. The utility

The "Longest Night": The Great Northeast Blackout of 1965

Early on the evening of November 9, 1965, as eleven-year-old Jay Hounsell wandered down a street in his neighborhood, he playfully smacked a telephone pole with a stick. Suddenly, the streetlights, the lamps and televisions in neighbors' windows, and all the other lights flickered and died. Jay went home and confessed his crime to his mother. Of course the youngster was not to blame, but that moment signaled the beginning of the most memorable power blackout in American history.

Just after 5:00 p.m., a seemingly minor series of equipment failures resulted in a massive overload that led to the failure of the entire electrical power network serving New York and the surrounding area. This failure plunged over 30 million people in the Northeastern United States into a complete electrical blackout.

Subsequent investigation revealed that a minor equipment failure had a "domino effect" on other pieces of equipment, cutting off a major power stream. Once that line was down, others became overloaded and failed. Within a few minutes the blackout had spread hundreds of miles. The network's built-in protective devices were supposed to prevent such a thing from happening, but were not capable of handling this particular set of circumstances. Part of the reason why the blackout was so widespread was the interconnection of power grids in the region. The interconnection of local power networks into a regional grid had taken place during the previous three decades. Such a grid was thought to be inherently blackout proof because when one section failed the others could, theoretically, take up the slack. The New York blackout dramatically demonstrated that such was not the case.

The twenty-three member companies operating the key transmission facilities for the grid, called the Canada-United States Eastern Interconnector (CANUSE), maintained their belief in the reliability of regional interconnection. They had in previous years demonstrated how entire power plants could be taken off-line for repairs without any noticeable change in power service, since the shortfall could be made up by other units in the network. This time, however, the built-in backups were strained past their capabilities by an improbable and unanticipated combination of factors.

The hardest hit area was New York City. Subways and trains rolled to a halt in the darkened tubes, leaving rush-hour commuters shivering in the dark. Elevators stopped between floors, trapping passengers inside. Traffic signals dimmed and failed, bringing Manhattan traffic to a standstill. Yet despite the potential for total mayhem, calm prevailed. When the power began to come back on the following day, stories began to filter out about the "disaster that wasn't," and the spirit of community that infused Manhattan residents that night. In the face of a frightening and dangerous situation, most New Yorkers rose to the occasion, remaining calm, polite, and helpful. One eyewitness wrote that

Within 10 minutes all major stations were on the air with continuous dialogue, soothing, calming, enjoining citizens to stay put and sit it out. Radio reporters interviewed civilians who had taken it upon themselves to stand in mid-Manhattan's streets and untangle traffic snarled by the blackout of traffic signals. Within an hour, all over the city, hundreds—young men, college boys, working men—were following the example. Then, again, by curious kindred response came the reports of singing in the street—on Third Avenue the sound of Christmas carols was heard.

Utility company employees were shaken by the event. Power plant managers and engineers found that such a total blackout made it much more difficult to get the system back "on line" than they expected. Some equipment was actually damaged because it was not designed with a total power failure in mind. Pumps feeding lubricating oil to the bearings in the "Big Allis" generator (see main text) cut off with the generator still in motion, and the lack of lubrication seriously damaged the huge machine. In some cases, power plants themselves relied on electricity to work, and without any power available, the boilers had to be manually lit. One engineer, Andrew Corry, recalled that

in Boston at the time of the blackout, we lost everything. We used wood—wood!—to start a furnace in South Boston. That's how we started and got back. Every other utility, I'm sure, has similar stories.

The power failure of 1965 was neither the first nor the last such occurrence in the United States, but affected more people than any blackout before or since. Short blackouts had been a common occurrence since the 1880s, but after 1945 outages caused by the weather or equipment failures were aggravated by the unprecedented demand for electricity. Utility companies were struggling to build power plants fast enough to keep up with growth in demand, and facilities often operated with small margins of reserve. The 1965 incident was unique not only because of its scale but also because it brought the issue to the level of public awareness. The power shortages of the 1960s were only the first in a series of postwar crises in electric power supply, marking the beginning of a period when electrical engineering would become a matter of public concern as never before.

"The Longest Night," *Newsweek*, 22 November 1965, 27-33; "Blackout Fallout," *Time* 19 August 1966, 40-41; John Lear, "The Night They Unplugged Society," *Saturday Review* 48 (4 December 1965): 81-84; "After the Blackout, The Questions," *Business Week*, 13 November 1965, 41-43; Theodore H. White, "What Went Wrong? Something Called 345 kV," *Life* 59 (19 November 1965): 51; Lurkis, *Power Brink*, 110; Interview with Andrew Corry by Loren Butler, 1 February 1994, IEEE Oral History # 185, p. 15.

companies faced new technical and organizational problems both in controlling power flows within these huge networks and coordinating their activities with those of other firms. Following a massive blackout in 1965, which affected much of New York City, the press and the Federal government lashed out at the power industry and the Consolidated Edison company, demanding that reliability be improved. When a second major blackout occurred just two years later in nearby New Jersey, the Governor of the state ordered utility managers to prevent such an occurrence from happening again. Suddenly public opinion figured into decisions previously considered only in technical terms.¹⁷

Public outrage over the issue of "reliability" struck at one of the basic assumptions of electric power engineering and

management; the public and lawmakers were, in effect, questioning the wisdom of dependence on large grids like the one supplying New York. But rather than suggesting that the grids be disconnected, industry experts argued that reliability could be increased only by expanding the grids even further. A single grid, they argued, could be controlled by a single organization capable of planning for contingencies such as failures and outages. The continued integration of electrical networks in the 1960s and 1970s required both technical and organizational innovations—though blackouts proved difficult to eliminate, as a second New York outage in 1977 proved.

Faced in the late 1960s with the prospect of having the government take on a new regulatory role, the U.S. electric power industry formed a new organization, called the North American Electric Reliability Council (NAERC), in the hope that a decisive corporate response to the “reliability” crisis would deflect the drive for new and unwanted governmental regulations. In the words of one industry veteran, “the lack of governmental understanding of the technology and the economics of power systems was of grave concern.”¹⁸ Thus the industry began to re-examine ways to increase reliability, both through engineering and through mutual cooperation.

The strategy successfully staved off some public criticism. In the wake of the blackout of 1965 there were no major restrictions on interconnection, and instead regulatory bodies deferred to utility managers and engineers, who now preached the gospel of system reliability. The industry pushed forward the formation of several regional pools, coordinated through the NAERC. By the 1990s, the North American system had been reduced to an even smaller number of individual grids, consisting of a giant cluster in the eastern part of the country, another in the West, and a separate Texas system, though in practice these three could share power amongst each other via buffered transmission links.¹⁹

3. GRID GENERATING TECHNOLOGIES

Interlocking grid arrangements reinforced certain technological trends, such as the preference for ever-larger power generating equipment. A rule of thumb that had held since the beginning of the century taught that no power plant in a network should account for more than 7 to 10 percent of total capacity. If a system violated that rule, and a larger generator failed, the strain on the rest of the network might

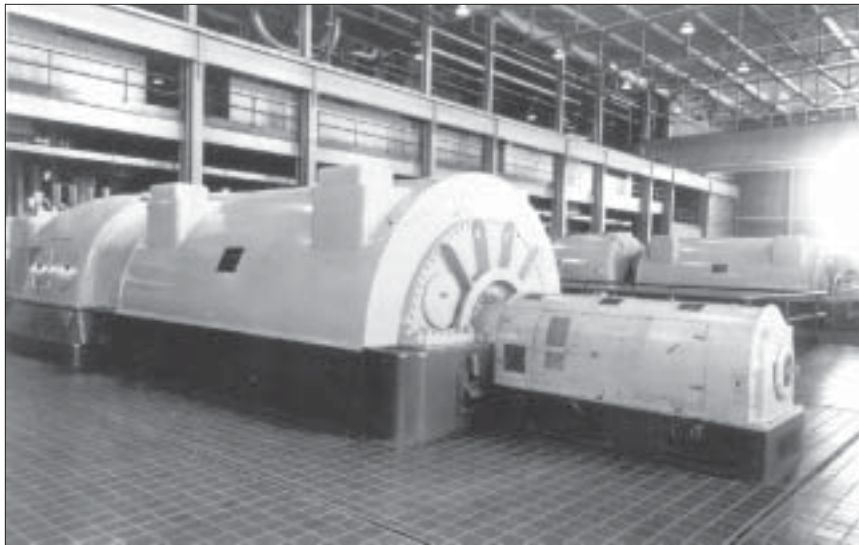
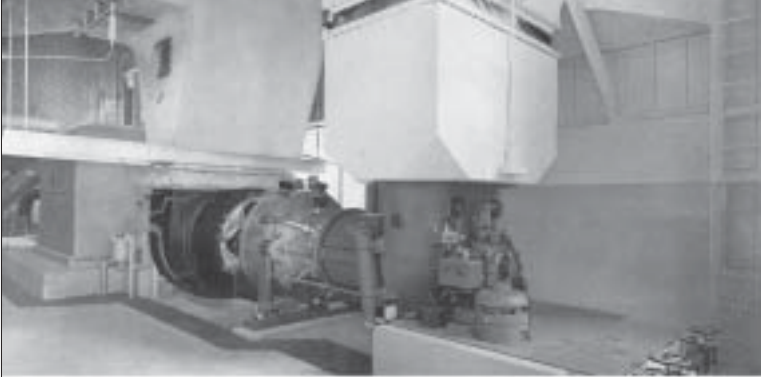


Figure 4. 30,000 kW General Electric steam turbine generator set, 1952.

be too great to bear. Integrating one or more systems in a “pooling” arrangement, by effectively expanding the size of the system, made breaking that rule justifiable. However, as integration of regional systems was taking place in the 1950s and 1960s, engineers designing boilers and turbines began to realize that additional gains in thermal efficiency could no longer be realized by enlarging existing designs, as had been done in the past. Offsetting the thermal efficiency plateau was the fact that fossil fuel costs dropped from the late 1950s through the late 1960s, reducing the economic incentive to find new sources of energy.²⁰

The efficiency of conventional power plants—those burning coal or oil in a boiler to produce steam to operate a turbo-generator—rose significantly in the first part of the century, but then leveled out at about 40 percent, meaning that most of the nonrenewable energy contained in fossil fuels was still being wasted. That figure has changed significantly in recent years. Still, the turbine remains the most popular prime mover, principally because it is the only available technology capable of supplying the vast demand for electricity. While other sources of motive power, notably falling water, have been widely used, in most countries the largest and best water power sites are already fully exploited.²¹

As demand grew in the postwar period, American utilities began supplementing their generating facilities with innovations such



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Figure 5. New technologies such as the gas turbine allowed utilities to add generating capacity in relatively small increments, but were generally more expensive to operate than larger coal-fired plants.

as the gas turbine, a petroleum-burning device similar to a jet engine that can be utilized intermittently to supply electricity at times of peak demand. However, this was a relatively small-scale—and often high-cost—option. Other peak load technologies included pumped storage of water at hydroelectric facilities where reversible turbines used to generate electricity actually pumped water back into the reservoir at off-peak times. But these technologies remained ancillary to the large, fossil-fuel-burning steam turbine, located in the central station power plant.²²

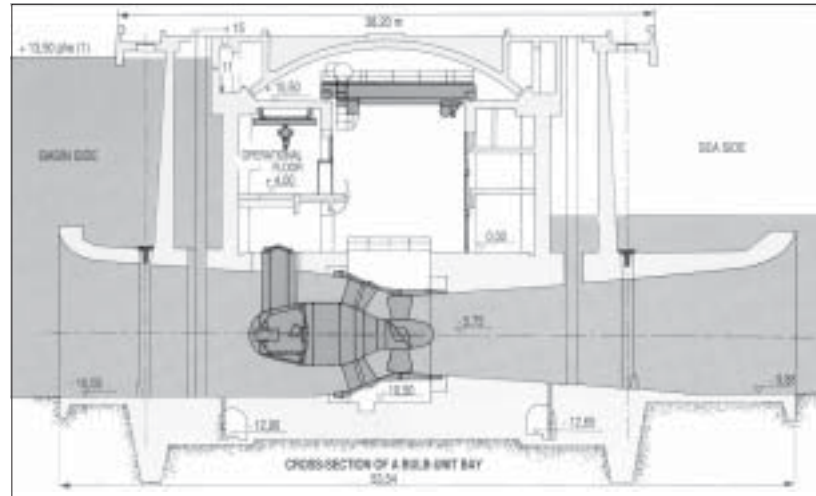


Figure 6. Cross-section of the “bulb” turbine generator used in the French EDF tidal power station.

Engineers also began experimenting with energy sources that avoided the use of fossil fuels. In the 1960s, for example, the French and others investigated the use of tidal currents for electrical generation. A large experimental tidal generating plant built on the Rance river in France in 1966 proved the viability of the concept, but the lack of other suitable sites thwarted its widespread use. Legislators, engineers, and others suggested a host of other possibilities. Geothermal energy for a time seemed like a possibility, as did the exploitation of thermal gradients in the ocean, but like tidal generation, power providers saw many of these alternatives as technically successful but of little practical value. The generation of geothermal energy, for instance, peaked in the United States in 1987 at only 1 million kW, a tiny fraction of the total.

The most important of these new technologies was nuclear power. The first commercial nuclear power plants were operated in the 1950s, and while nuclear power was widely hailed as the energy source of the future, it was years before nuclear plants contributed a sizable portion of the total energy production in any country.²³

In the political aftermath of Hiroshima and Nagasaki, American scientists, military leaders, and politicians began looking for a way to promote the peaceful uses of atomic energy. While the United States

was the first to develop the atomic weapon, it was its rival, the Soviet Union, which launched the first successful atomic-powered electric generator in June 1954. This small plant had a capacity of only 5 MW but demonstrated the viability of nuclear generation. American and European governments, embarrassed by this Soviet triumph, stepped up their efforts to establish nuclear plants.²⁴

Military pressures in the United States, especially the desire to make nuclear generators for submarines, helped lead the General Electric and Westinghouse companies into the design of commercial atomic reactors. The two companies adopted somewhat different technologies, one using pressurized water as a coolant and the other, sodium. Some versions of nuclear power technology proved to be very successful immediately, particularly the power plants used to provide mechanical power for ships and submarines (an early proposal for a nuclear-powered airplane was abandoned). These were small nuclear reactors coupled to conventional steam turbogenerators. Other applications proved less feasible, such as the small, self-contained nuclear generating plants installed at remote military bases in Greenland, Wyoming, and the Antarctic.²⁵ Having accumulated a wealth of experience in building military nuclear devices, these firms made a relatively smooth transition into the building of civilian nuclear power plants by the early 1950s.

In 1953, the Eisenhower administration approved a plan to have Westinghouse and the Duquesne Light and Power Company jointly develop such a plant, and the result was the Shippingport, Pennsylvania, 60 MW plant that opened, or "went critical," in 1957. When utilities proved reluctant to adopt nuclear power, General Electric provided a demonstration plant at the fixed cost of \$66 million to the Jersey Central Power and Light Company in 1963.²⁶

European countries, some with the assistance of the United States but others with its pronounced disapproval, also experimented with nuclear fission for both weapons and power purposes after World War II. Great Britain, in fact, achieved near self-sufficiency in energy production in part due to its extensive nuclear program. The early British reactor technology was somewhat distinct from its American counterparts in using air as a cooling medium (although a reactor of this type was eventually built in the United States at the Brookhaven research center in New York). By the late 1950s, the British had two reactors on-line producing fuel for both atomic weapons and electricity.

The French also developed this dual-purpose type of nuclear technology by the mid-1950s,²⁷ which became the basis for an ambitious program of economic and military independence.²⁸ French engineers developed a standardized reactor design that could be made quickly and cheaply, and soon France became the European leader in nuclear power production. By the 1980s, more than 75 percent of French electricity production came from nuclear plants. Canada and several European countries including Germany, Switzerland, Spain, Italy, the Netherlands, Norway, Finland, and Sweden also developed nuclear technology in later years, as did Japan, China, India, and several others.²⁹

4. GRID TRANSMISSION TECHNOLOGIES

Besides generation, other technologies in use in the industry saw significant but incremental change during the postwar period, most of it also related to the drive to expand power grids. The most notable characteristic feature of transmission equipment for this period was the fact that it extended prewar accomplishments. That is to say, transmission voltages climbed higher, and maximum economical distances grew longer. Already having reached 300,000 volts during the War, the highest practical voltage jumped to 735,000 in 1965 with the building of a special line across the St. Lawrence River in Canada, and then to nearly 750,000 volts by the early 1980s.³⁰ Along with a range of other technologies and regulatory changes, high-voltage transmission allowed the formation of inter-regional networks spanning over a thousand miles in the United States, and the economical transmission of power from isolated plants to load centers over equally great distances in many other countries.³¹

The electric power system had become so vast in industrialized nations by World War II, and the cost of operating it so high, that seemingly minor technical changes were among engineers' greatest concerns. Engineers expended much engineering creativity in the postwar period making improvements to existing technologies in order to squeeze out relatively small increases in efficiency, which translated into huge savings or larger corporate profits. However, these incremental changes often required a huge engineering effort because of the integrated nature of the power grid. Using a significantly higher transmission voltage, for example, required that each component in a very large system be redesigned. Merely raising the voltage on a line instantly made obsolete a whole range of technologies, from



Figure 7. Banks of General Electric thyristors used at a converter station in Stegall, New Hampshire.

transformers to insulators to transmission towers. Nonetheless, an efficiency increase of even a fraction of a percent was important because it translated into many millions of dollars in savings.³²

An entirely new line of development in the field of transmission was known as power electronics, and it involved the use of electron tubes and semiconductor devices as part of the transmission and distribution system. Most early power electronics devices were applied to the use of high-voltage direct current (hvdc), a technology which

Superconductors: The Transmission Engineer's 'Manhattan Project'

Most of the large-scale research and development programs in the electric power industry have involved new technologies of generation, such as nuclear fission, fusion power, solar cells, and others. However, the field of transmission has its own "Manhattan Project" aimed at producing a commercially viable superconducting transmission line. Heike Kamerlingh Onnes discovered the superconducting properties of certain metals in 1911. Research undertaken in England in the 1950s produced a class of superconductors suitable for high current transmission, but the cost of cooling them to almost absolute zero made commercial application impractical.

Utility companies began building short, underground, refrigerated, pressurized transmission lines partly as a way to avoid building unpopular overhead lines in cities. Consolidated Edison Company in New York, for example, put into service a short section of a 345 kV refrigerated line in the late 1960s. Beginning in the late 1960s and early 1970s, research on superconducting or cryogenic cables expanded, in part due to funding from organizations such as the Atomic Energy Commission and the National Science Foundation in the United States. Engineers have made considerable progress in recent years. Early superconducting materials required extremely low temperatures to function properly, but by the 1980s "high temperature" superconductors were available. Despite this, practical, long-distance superconducting lines have proven elusive, and the deregulation and slower growth of the electric power industry in the United States since the 1980s has proved to be a major setback.

Taylor Moore, "Superconductors are Still Hot," *EPRI Journal* 17 (September 1992): 4-15; Donald P. Snowden, "Superconductors for Power Transmission" *Scientific American* 226 (April 1972): 84-86.

re-emerged as a competitor to alternating current in the postwar period. The so-called Battle of the Currents in the late 19th century, which pitted Edison's original dc system with the ac system promoted by Westinghouse, AEG, and others, was essentially decided by 1920. Alternating current emerged triumphant in part because the state of the art in dc technology could provide no counterpart for the transformer, a simple device that allowed ac voltages to be raised or lowered economically for transmission purposes. Direct current can be transmitted along wires with great efficiency, and—all other things being equal—low-current, high-voltage electricity (ac or dc) can be transmitted at a lower cost than high-current, low-voltage electricity. Simple transformers became available at the turn of the century to convert ac energy to high voltages and reconvert it to voltages usable by consumers, giving ac systems an important commercial advantage, and partly explaining why ac triumphed over Edison's original dc technology. Further, transformers made it possible for a single generator to supply customers with various voltage requirements: thousands of volts for transmission, 500 or more volts for industrial

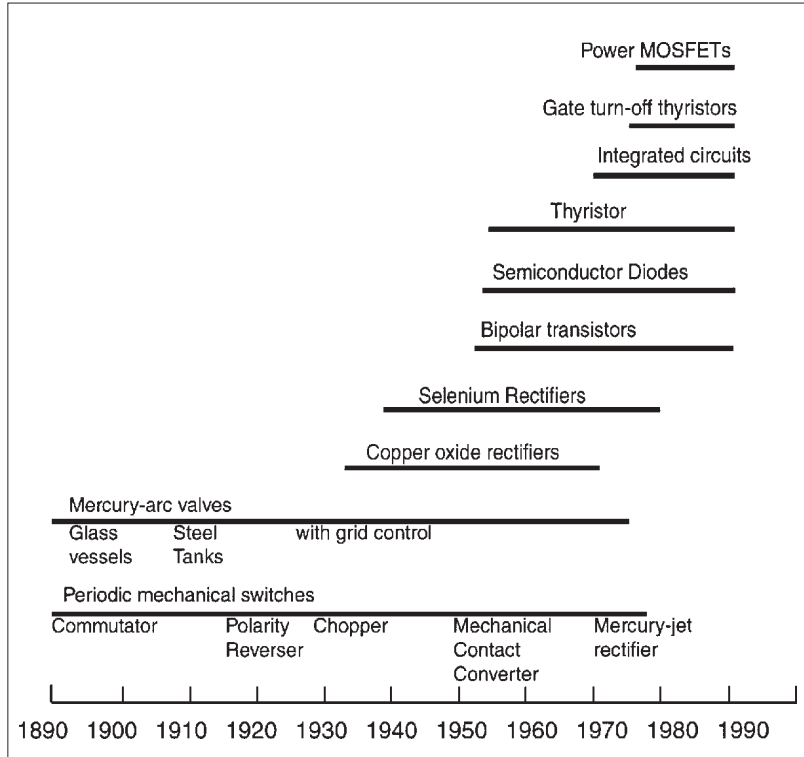


Figure 8. Approximate dates of introduction and obsolescence of some of the electronic devices used in power applications, as of 1985.

purposes, 115 volts for domestic lighting, and so on. Finally, by using transformers, electric utilities were gradually able to raise transmission voltages to the point where transmission over hundreds of miles was economically feasible. This meant that not only could large urban areas be served by central stations (which was the initial justification for this technology) but that distant cities or areas could be linked.³³

While most commercial power plants built after 1900 delivered ac, direct current service never completely died away. Some areas which were supplied with Edison dc systems early on, such as parts of Great Britain, simply did not update equipment. Parts of many large cities in the U.S. and Europe, including Chicago and New York, had dc service at least through the 1950s. In rural America, small dc generators were installed on farms through the early 1940s to supply power for commercial and domestic equipment.

Dc power plants also remained in service for supplying older or special-purpose industrial motors, such as those used in steel mills, and for electrolysis operations such as zinc, aluminum, and hydrogen production. Sometimes, industries requiring dc power generated it on-site, but more often they purchased ac from a utility and converted it to dc. Until about the 1930s, the dominant technology for doing so was the electromechanical "rotary converter." But by the late 1930s, vacuum tube converters were available which offered higher levels of efficiency. One of the bridges between turn-of-the-century dc power and current work in the field was the electrification of existing railroads in the U.S. and Europe, which began in the late 19th century and continued until after 1945.

Electrical equipment manufacturers in the United States that were interested in high-power electronic devices were primarily oriented toward this railroad market. One of the leading firms in this field was the General Electric Company, a firm with roots in the old Edison Electric Company and with a growing strength in research and development after 1900. Power electronics at General Electric had its origins at the turn of the century in work on high-current mercury-arc rectifiers. A rectifier is a one-way valve which converts an alternating current to pulses of direct current, making the power suitable for operating dc devices. Around 1904, GE was seeking improved methods of arc lighting and needed a way to convert ac power, by then widely used, to dc power suitable for their "magnetite" arc lamps, and this line of inquiry led to the first such rectifiers.³⁴

While the mercury-arc rectifier later proved to be a satisfactory way for electric railways to obtain dc power from commercial ac sources, it also encouraged experimentation with other high-power, high-voltage electronic devices. Since 1945, power electronics has proven to be one of the fastest growing fields of research, especially since the introduction of semiconductors. Electric railroads were early users of semiconductor devices, especially the copper oxide rectifiers of the 1930s, which performed the same type of ac-to-dc conversion as mercury-arc rectifiers. Later, the railroads also became the primary users of large selenium rectifiers, presaging the widespread use of selenium diodes in electronic equipment.³⁵ Yet small, efficient electronic devices for power system use took many years to develop. R. N. Hall announced the first high-current germanium diodes in 1952. These devices were capable of handling 35 amperes of forward current and withstanding a reverse voltage of 200 volts—high ratings for a germanium device but still of limited use in power grids. The maximum voltage levels under which semiconductor devices could

operate gradually rose in the 1960s, especially after the introduction of new fabrication techniques such as diffused junctions.

By the 1960s, high-voltage/high-current semiconductor rectifiers that could be controlled in a fashion analogous to a vacuum tube or transistor were being marketed by General Electric and other firms. This device, called the Silicon Controlled Rectifier, was a modification of the p-n-p-n transistor first developed at Bell Laboratories for telephone work.³⁶ Semiconductor devices, which in the 1940s were limited to very low voltage and power levels, soon saw increasing adaptation to power purposes. Bipolar transistors capable of handling 20 amperes were available by 1970, and just a few years later they could reliably control 400 amperes.³⁷

Power electronics moved ahead rapidly in Europe and the Soviet Union, and particularly in Scandinavia, where good sites for hydroelectric or mine-mouth generation existed but at such a distance from the cities that even high-voltage ac transmission had been deemed too inefficient. The introduction of vacuum tube rectifiers and grid-controlled "inverters" for converting between dc and ac helped changed engineers' notions about the viability of these sites and about dc transmission. While work on mercury-arc rectifiers had been going on at the Swedish firm ASEA since 1932, it was not until 1940 that the company applied its knowledge to a practical dc power system. The firm, with the aid of the Swedish power authority, designed a 36-mile line between the towns of Mellerrud and Trollhattan to transmit 6,500 kW at 90,000 volts. ASEA subsequently became a leader in conversion and transmission technologies.

Power electronics would come to play a role not only in long-distance transmission but also in the linking of power systems into larger networks by matching systems with different standards. Between the late 1930s and the early 1940s, for example, several European and American companies experimented with electron tube devices for frequency changing purposes. Here, ac power at one frequency was converted to dc, then reconverted to ac at a different frequency. In this way, mismatched alternators could be placed into service in the same system, or equipment requiring an odd frequency could be supplied from a standard ac source, and thus smaller power networks could be linked to form larger ones.

Examples of this work included an installation in 1943 by the Allis-Chalmers Manufacturing Company in which a mercury-pool rectifier and inverter matched the 66,000 volt, 25 Hz power developed

Electricity and Health

Public concern over the health hazards associated with electric power shifted dramatically in the post-1945 period. From the late 19th century on, accidental electric shock had been the power industry's only public health concern. However, the environmental, consumer, and anti-nuclear movements introduced new challenges in later years. In the 1960s and 1970s, utilities responded to federal anti-pollution mandates by installing smokestack "scrubbers" and other technologies. By the mid-1970s, the chemical PCB, which was a component of the oil used in large, oil-filled transformers, was shown to contribute to cancer. The United States Congress banned the use of PCBs in transformers in 1977, and later ordered that existing transformers be cleaned up. Large transformers occasionally catch fire, and cleanup after the burning of PCB-laced transformer coolant could be costly. In 1981, for example, the City of New York spent approximately \$28 million to clean up an office building contaminated by dioxin from a basement transformer that burned. Several years later, more than half of the 57 transformers located in various Smithsonian Institution museums were found to be leaking PCB-tainted oil, meaning that if a fire broke out it might have contaminated "the nation's attic" with deadly dioxin. The coolant in the transformers was subsequently drained and replaced. The electric industry's woes did not stop there. In the late 1970s, there began a series of protests against high voltage power lines, both from people who believed the lines cause cancer and from those who objected to the way they blighted the natural environment. The most famous protest involved Minnesota farmers, who went so far as to damage a newly built hvdc line in 1980. Through the 1980s, scientists undertook many studies of the health risks of exposure to electromagnetic fields, some of which linked electromagnetic fields to cancer. Most studies dismissed such risks, but by now some members of the public felt threatened by the perceived risks of devices ranging from kitchen appliances (especially microwave ovens) to electric blankets. The debate over possible health hazards associated with electromagnetic fields continues, but it will be years before conclusive results are available.

by privately owned generators at the Carnegie-Illinois Steel Company to a public utility network rated at 132,000 volt, 60 Hz. Similar setups installed in Germany in 1932 (converting 50 Hz power to 16 2/3 Hz) and in Switzerland in 1938 (converting 50 Hz to 40 Hz) both served to provide power for electric railways. The Swiss installation was in continuous duty through 1960.

Power electronics was also important in long-distance direct current transmission. The German companies Siemens-Schuckert A.G. and AEG developed experimental underground dc transmission technology during World War II. A route planned through the Alps and further experiments were abandoned as the war drew to a close in 1945. Following Germany's defeat, the Soviets took the experimental equipment and relevant documents in 1945 as reparations, presumably using them as part of ongoing hvdc experiments in the Soviet Union. By 1950 the Russians had opened a line between Moscow and the city of Kashira, approximately 65 miles away. This

underground line developed 120,000 volts dc and was converted into 110,000 volts ac at Moscow using Russian-made converter tubes. The trial was so successful that in 1956 the Soviet government announced plans for an 800,000 volt, 750,000 kW line 300 miles long between Stalingrad and a mine-mouth power station near the Crimea.

In the early postwar years, the new power electronics devices began to be included in proposed long-distance transmission systems, since now they offered the opportunity of easier interconnection with ac systems or conversion to different dc voltages. ASEA, encouraged by incentives from the Swedish government, made a 29 MW, 100 kV hvdc connection in 1954 to the island of Gotland, 60 miles from the mainland. The Gotland installation, incidentally, was one of the first to use semiconductor devices to convert dc to ac. The English Central Electricity Generating Board also resumed prewar research in hvdc transmission after 1945, and by 1950 formed a joint committee with the French organization EDF to build a 200,000 volt link across the English Channel, using equipment supplied by ASEA. That line opened in 1961, supplying 160 MW at 100 kV, and later was replaced by a 2000 MW line.³⁸

Many such links have been made since 1960. Italy, for example, linked its mainland grid to that of Sardinia via a 100 kV dc line in 1965. The same year the Japanese opened two such lines. Such systems could also provide a measure of isolation from a grid partner considered unreliable in either the technical or political sense. Finland's power grid, for example, was connected to that of the Soviet Union's via an ac-dc-ac conversion in the early 1970s, opening up new possibilities for trade in electric power but isolating Finland's system from the potential threat of a politically motivated cut-off.³⁹

American interest in hvdc revived by 1964, and several utility companies and equipment manufacturers began testing updated versions of this technology. Having deemed power electronics as finally "ready" for commercial service in the United States, American utilities began to devise formulas for calculating the minimum distance at which hvdc would be economical. To date, the most ambitious hvdc project in the United States was built not by a private utility, but by the United States government in the form of the Bonneville Power Administration's Pacific Northwest-Southwest Intertie system, authorized by Congress in 1964. The first two 750 kV lines of the system were put into operation in 1970. Federal involvement in hvdc research has also involved the funding of

research and development efforts. By the early 1980s, spurred by Federal government research dollars, General Electric had developed hvdc equipment that could handle up to 800 kV.⁴⁰

A second example of new transmission technology related to electronics, but which was not a commercial success, was the wireless transmission of power. While energy transmitted at broadcast radio and television frequencies spreads out as it travels away from the transmitter, at microwave frequencies it is easier to focus energy into a beam. This type of wireless, high-frequency transmission of power began to receive a great deal of attention after 1945, after a period of intense war-related development of electronics technologies. Microwave transmission of small amounts of energy reached a high state of development for other purposes such as radar and communication in the 1940s. By the 1950s, AT&T was setting up a national network of microwave relay stations to transmit long-distance telephone calls. However, wireless transmission of large amounts of power was considered too inefficient to take seriously. By the 1970s, however, in part through the support of the Federal government, microwave power transmission was again being investigated as a substitute for copper wire.

Like dc transmission, wireless transmission had a long history of development before World War II. Nikola Tesla, best known for his work on ac generators and motors, was also deeply interested in the transmission of power without wires. Though hampered by the lack of a steady source of current, Tesla, in the late 19th century, experimented with high-frequency, high-voltage ac generators and proposed a system of wireless power transmission.⁴¹ Numerous inventors imagined similar systems, but available radio transmitters could not provide an intense, focused beam of power until the development of radar equipment in the 1940s.⁴²

While the transmission of microwave power, particularly through special conductors called waveguides, was commonly used for a variety of communications purposes after World War II, through the 1960s communication was the only commercial application of the transmission of microwaves over long distances. Two army engineers, writing for a 1968 textbook on the subject of "free space beam transmission," concluded mathematically that microwave transmission was so inefficient that huge antennas would be required to transmit and receive enough power to operate even a small device such as a satellite. The antennas necessary for a

communications satellite, they concluded, would have to measure at least 2.3×10^5 square meters.⁴³

However, the use of microwave transmission for powering small machines began to seem feasible during the late 1950s when microwave tubes capable of transmitting over a hundred kilowatts appeared. Owen Maynard and William Brown of the Raytheon company, for example, designed and built a system in 1963-64 that could beam power to an electrical helicopter, keeping it aloft. This proposed aircraft was part of a Cold War plan to build observation or communications platforms which, like space satellites, could be kept in the air indefinitely. NASA, Raytheon, and the Jet Propulsion Laboratory later sponsored a significant research project aimed at doing quite the reverse; using a solar powered transmitter in space that would beam microwave energy to earth.⁴⁴ The initial proposal came from Peter Glaser of the Arthur B. Little Company in 1968, and various aspects of the plan were treated in a 1970 special issue of the *Journal of Microwave Power*.⁴⁵ By the mid-1970s, the Jet Propulsion Laboratory was conducting tests to determine the efficiency of high power microwave transmission over great distances. Although institutional funding sources and research sites changed, research continued into the 1970s before ending in 1980 after its NASA and Department of Energy funding was cut off. Since that time, the Japanese government has undertaken a solar satellite project intended to be operational by 2000, but elsewhere interest has flagged.⁴⁶

It is clear that much of the history of transmission technology development can only be appreciated in the context of the power providers' drive to build ever-larger grids and to solve the problems of long-distance transmission. With greater grid integration came a host of new technologies, many aimed at controlling these growing systems. A key technology was the computer. The "computerization" of power generation took two main paths: the modeling of power system behavior, and the control of actual pieces of equipment. The first use had prewar origins, though the second was entirely new.

5. GRID CONTROL TECHNOLOGIES

Computerization was preceded by developments in technologies used to regulate, switch, and monitor the grid. The importance of these technologies has grown in proportion to the increase in the

size of central stations and the length of transmission lines. The technical approaches that engineers chose in addressing the problems of control and regulation ushered in a dramatic new era in power engineering based on the use of electronics.

The rapid growth of power systems required sophisticated devices to monitor and remotely control equipment. Any electric power system necessarily requires devices for switching and overload protection at the terminal points of power lines—including the generating facility—at points along distribution lines where transformers are located, and even at the customer premises. The earliest systems were entirely manual, but in the late 19th century engineers developed electromechanical devices capable of operating automatically. In the post-1945 period, as the transmission lines for “bulk power” shipments got longer and networks increased in complexity, the demands on the protection and relaying devices grew. Earlier electromechanical devices could detect various kinds of transmission failures and automatically open switches to protect generators from overload. In the postwar period, through the use of new designs as well as new technologies such as electronics, these devices became more



Figure 9. The Anacom analog computer was used to simulate complex electric power networks.

sensitive, operated more quickly, and eventually worked in conjunction with central computers.

One of the major developments of the 1960s was the improved underfrequency relay, a device which detected the slight drop in frequency which would accompany certain conditions, such as the failure of a generator in an alternating current power network. The operation of larger grids demanded that all generators be locked "in step," generating current at exactly the same frequency and all in phase. By the 1970s, underfrequency equipment was supplanted by digital electronic devices performing essentially the same function, while in the 1980s, active protection devices and fiber optics technology offered increased reliability and the possibility of resetting tripped equipment according to stored programs.⁴⁷ Greater stability of the system was necessary for reliable operation, but also came to be important to electricity customers. More and more customers who owned computers demanded "clean" power, free of voltage and frequency changes, since even momentary power outages began to have more serious consequences than in the days when consumer loads were limited to electric lights and motors.

In the 1930s, when networks had become so large as to be almost unmanageable by their operators, the electrical manufacturers devised new ways to control the grid based on simulations performed on analog computers. These devices consisted of models with small generators, inductors, capacitors, and variable resistors used to simulate full-size generators, transmission lines, and loads. These were used to determine how and when to switch generators in and out of the grid over the course of the working day, that is, to determine the most "economic dispatch." Typically, a power utility owned or had access to a surplus of generating capacity; only infrequently was the load so great that all generators were operating at full capacity. Further, utilities found it desirable to have excess generating capacity above and beyond the maximum expected load, so that generators could be taken off-line for periodic servicing. A centralized load dispatching office using a "network analyzer" simulated the actual network, and could be used to determine the most economical combination of generators to put in service under various load conditions. Then dispatch workers could contact operators of various machines in the network to provide instructions.

The network analyzers of the 1940s grew increasingly more sophisticated, incorporating the capability to calculate transmission losses in addition to economic dispatch. Many universities just after



Figure 10. One of the keys to making large grid systems work was accurate synchronization of generators. The maintenance of voltage and frequency within close tolerances also made devices such as electric clocks more accurate. The problems of providing “clean” power grew even more critical as more customers began using computers and electronics.

World War II also built such analog computers, and often these were the first computers that universities owned. These were not usually used for dispatch purposes, but for planning additions to the system or testing theories about system operation. The computers generated

interest, research opportunities, and occasionally some revenue for the organizations that owned them. However, in the early days the benefits to power companies of this kind of computing were not always clear. Lionel Barthold, an engineer at General Electric, found that the high cost of computing made it difficult to "sell" the service to companies at first. However, through a clever strategy, GE found that its computing service practically sold itself.⁴⁸

If you go to an engineer in Ohio Edison Co., for example, and say "you know, you really ought to study that problem on an analyzer, and, by the way, there's no charge," the answer would be "go ahead, here's the data." On the other hand, if you tell him "that's going to be twenty-six thousand dollars," he would say "I've got to get approval." He would then go to his boss in a selling effort and say "these guys at GE are the smartest people in the universe, we can't live without them." So all of a sudden people were selling your organization inside their company because they had to justify the work.⁴⁹

Many utilities employed analog computers for plant operations through the 1960s. Yet even as the acceptance of these computers was growing, the technology of computing was changing, moving away from the original analog simulators and toward digital designs that could be used not only for simulation but for actually controlling plants or equipment. While analog computers are still used today for solving certain types of problems, their numbers are few.⁵⁰

By 1965, computers were in use in the direct control of some of the functions of power plants which had previously either been under manual or mechanical control. Using a combination of analog and digital sensors, analog computers, and analog-to-digital converters, a computer in the plant's central control room could monitor and adjust boiler fuel feed, air intake, feed water, steam temperature and pressure, and other boiler or turbine operations. One such early computerized plant was the Jack McDonough plant of the Georgia Power Company, where a coal-fired boiler fed two 250 MW turbogenerators. An online digital computer monitored plant operations and operated the boiler controls.⁵¹

Engineers soon extended this by employing a centralized computer control not merely for a single switch or power plant but for a group of plants, switches, or other remote equipment. A hybrid digital-analog system of this type, put in place by the American Electric Power company in the mid-1960s, used analog computers to control

There's Still a Dimout in Western Kansas

On two-thirds of all Great States' farms, children still read in the dimness of old-fashioned lights, women keep their work longer and harder without the help of electric light, vacuum, radio, running water... Of the helping hands of electricity... have been denied their electricity since the green, and hard power plants have been built and in operation. Farms, build and manage.

Now, BARDCO offers a revolutionary program for the electrification of farm communities. Local communities are pleased to have an entire generating and distribution system "workable" of lowest electrical power is available to assist.

All that war has taught the electrical industry about efficient generation of electricity and its fullest use through modern appliances will be combined with tomorrow's management and construction facilities.

BARDCO Generator Sets, from 2 to 300 KW, now serve the Armed Forces in all parts of the world—are presently available for rural electrification and industrial applications.

BARDCO MANUFACTURING & SALES COMPANY
LOS ANGELES • DAYTON • WASHINGTON, D. C.

Figure 11. One result of World War II was increased sales of relatively small diesel generator sets to the military. After 1945, equipment manufacturers tried to sell them to farm communities, but were not widely successful.

economic dispatch for 6000 MW of power from fifteen separate plants. The analog part of the system regulated frequency and controlled power interchange with other systems. Digital computers were used not only for data processing and billing, but also for certain control operations, using microwave-based telemetering equipment and digital communications to receive operating data and issue control instructions to remote substations and other facilities. An automated

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COOLS ANYWHERE!

MOUNTS IN UPPER WINDOW
Flip Rack... lets in cool air... stops heat from coming in.

MOUNTS IN LOWER WINDOW
Just 18" tall... 18" thick... doesn't stick out... and on in!

MOUNTS TIGHT TO WALL
Mounts flush—lets in the window clear and seals around... prevents hot air from coming in.

Vornado TWIN-THIN ROOM AIR CONDITIONER

Vornado's new, rolling, portable Twin-Thin gives you the versatility of several air conditioners—for the price of only one! It's portable! Cools living areas by day... sleeping areas at night. Rolls easily from room to room on a convenient and attractive stand... adjusts to suit most windows!

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for every need
Vornado
just cools better!

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Figure 12. Domestic energy usage swelled in the postwar period as more and more electric devices entered homes. One of the most popular products was air conditioning, invented years earlier but popularized in the 1950s and 1960s.

control system installed by the Japanese company Tokyo Electric in 1979 was typical of the systems being proposed or designed during the 1970s and 1980s. In this system, a computer dispatch center could control up to fifty substations using advanced telemetering and communications technologies.⁵²

Remote control and automation of electric power plants, distant power substations, and transmission facilities was important for the success of the "inter-regional" grids in the United States, in part because they increased the reliability of these systems and helped power companies avoid large-scale outages. The Bonneville power district in the Pacific Northwest region, for example, a largely government-funded enterprise, joined its network with that of Pacific Gas and Electric and several other utilities during the 1960s to create a giant Pacific Northwest-Southwest Intertie. This network, like similar efforts in the industrialized Midwest and Eastern United States, in Western Europe, and in the Soviet Union, was simply a geographic extension of existing regional grids, but its operation was substantially more complex. By the 1970s, there was talk of a single, national grid in America, or even an international network. These complex, geographically dispersed systems relied heavily on computers and automated control.⁵³

6. COMPLETING THE GRID

Industry in the United States and many parts of Europe was well served by electric power by 1945. All that remained was to replace the remaining non-electric industrial steam engines and water wheels with electric motors, and extend electric lines to isolated rural areas. Many water-powered factories were abandoned or their turbines retrofitted to allow hydroelectric generation. However, a surprisingly large number of households, even in industrialized nations, still had no electricity, and compounding this problem was the fact that most were located in rural areas. As late as 1944, for example, only 55 percent of U.S. farms had access to electric service. Private utilities insisted that extending service to these rural customers would be unprofitable, and refused to build the necessary lines, but the Federal government's Rural Electrification Administration made rapid progress in subsidizing service for these customers. The agency provided low-cost loans to consumer cooperatives that allowed the construction of lines to connect homes to existing commercial power grids, and by 1962 nearly 97 percent of farms were connected.⁵⁴

One of the most ambitious rural electrification projects of the pre-World War II period, the Tennessee Valley Authority (TVA), persisted into the postwar era and took on worldwide significance. The TVA, a Depression-era program begun under Franklin Roosevelt, had as its aims not only rural electrification but navigational improve-

ment and flood control. Between its inception in 1933 and the end of the war, the TVA built over a dozen major dams and several smaller ones on the Tennessee, Cumberland, and other rivers in Kentucky, Tennessee, North Carolina, and Alabama. Seven other, smaller dams were completed between 1945 and 1970. In all, twenty-nine of these dams included hydroelectric facilities, with an installed capacity of well over three million kilowatts.⁵⁵

In some ways, the TVA became a victim of its own success. By actively promoting the use of electricity and selling it at about 25 to 30 percent of the average rate, TVA customers soon demanded more electricity than the network of hydroelectric dams could produce. The Agency began building thermal plants, first coal-fired and later nuclear types. As the TVA became a large and unwieldy bureaucracy, its mission of regional development was overwhelmed by its role as a power company, its coal-fired plants were cited as major sources of pollution, and its nuclear plants eventually faced the same daunting problems as those of commercial utilities. All this led to severe criticism of the organization by the 1970s. However, the TVA model of planned regional power development became the model that non-industrial countries emulated as they sought to create an electrical infrastructure quickly and cheaply.⁵⁶

Chapter 2

Worldwide Electrification from the 1950s to the 1970s

1. REPRODUCING THE GRID IN NON-WESTERN COUNTRIES

The electrification of non-Western countries had proceeded at a very slow pace in the period before 1945, but postwar international agencies promoted the idea that these countries would inherit the best of what Western engineers had developed. Electrification had indeed widened the rift between industrialized nations and the rest of the world. At the end of the war, no non-Western country had a level of household or industrial electrification that matched even the least-developed Western nations. But after 1945, with the onset of the Cold War, there was a surge of economic development activities sponsored by industrialized countries aimed at cultivating allies overseas by providing them with the tools they needed to “modernize” their economies. The United States, because of its vast economic resources, was at the forefront of this effort. Through international agencies such as the World Bank, the International Monetary Fund, and various unilateral or multilateral agencies, the West funded thousands of infrastructure improvements. Similarly, the Soviet Union and, to a lesser degree, the People’s Republic of China funded or supplied technology for numerous projects in foreign countries.

The theories of economic development fashionable at the time taught that when nations were supplied with basic services, such as transportation, communication, and power, they would begin to develop Western-style economies on their own. The Tennessee Valley Authority, particularly the TVA’s power grid, was frequently held up as a model. The TVA’s former director, David Lilienthal, personally promoted the TVA model of develop-

ment after 1955 when he helped organize the Development and Resources Corporation, a private company that undertook engineering projects all around the globe.⁵⁷ The World Bank, another international development agency, was established in 1945 to bring stability to international capital markets through the making of large loans. By the provisions of its charter, its loans were to finance specific development projects. Since 1948, the World Bank (as well as affiliated institutions such as the International Finance Corporation) has sponsored dozens of electric power projects in Africa, Asia, Central and South America, and even Europe.⁵⁸ Unfortunately, economic theories, Western technology, and capital infusions had mixed results when applied in various countries around the world.

2. CASE STUDIES FROM INDIA, SOUTH AMERICA, AND AFRICA

India, for example, was an area already partly “modernized” by centuries of British colonialism. It had a network of rail and water transportation, mainly oriented toward commercial traffic, extensive plantation agriculture, and some factory production. But in 1945 there was still little in the way of electrification, and so technical aid projects, mostly run by Americans, were initiated to electrify Indian farms. By the 1970s, the most common use of electricity in rural regions in India was for driving irrigation pumps and, to a lesser extent, operating other agricultural machinery. Electricity seemed to contribute to the growth of small, rural businesses, which often used the power for lighting to allow work to be carried on after dark. Other businesses used electrical machinery to carry out production operations, particularly in the case of grist and saw mills. Some studies indicated that the quality of life in certain respects changed considerably for rural families following household electrification. Families surveyed in India indicated that reading, especially among children, had increased. The material wealth of families with household electric service grew rapidly. Most of these families, at least in the 1970s when several surveys were undertaken, purchased electric irons and radios soon after receiving basic lighting service, and sewing machines and televisions were not far behind.

Yet the effects of electrification were not always beneficial, or even predictable. While reading increased in India, in Colombia many families reported only that television use had increased but reading had not.⁵⁹ The lifestyle changes made possible by the availability of electricity tended to amplify existing social distinc-

Case Study of Electrification: China

The electrification of non-Western countries in the postwar period cannot easily be summarized, because every country's experience was unique. While much of the world's population still has limited access to electricity compared to the United States, some developing countries did have considerable success in electrifying in the post-1945 period. Typically these were areas with a more advanced base of Western technical knowledge at the outset of the postwar period, but in several cases they broke away from the American style of centralized power production. One such example is China. The first major expansion of China's generating capacity came during the period when Japan occupied Manchuria. It was the Japanese who built the first large hydroelectric and coal-fired generating plants in China, at Supung and Fengman. After Japan was defeated in World War II, its presence was partially superceded by the influence of the Soviet Union. Just after the war, the Soviets partially dismantled the powerhouse at Fengman, reducing its capacity from 564 MW to 144 and causing enormous hardships for the Chinese.

Between 1950 and 1959, however, China expanded its electric generating capacity considerably. The Fengman powerhouse was restored to the original rating, and with international assistance from the Soviet Union and Czechoslovakia the total Chinese hydropower capacity had risen to 1000 MW by 1957. China had the world's largest reserves of potential hydropower, and dozens of projects were planned during the Great Leap Forward of the late 1950s. Most, however, were abandoned soon afterward or delayed because of continued political turmoil. Through the 1960s, almost all of China's electricity production (totaling about 60 billion kWh) was from thermal generators. It was not until the 1970s that several of the projects begun in 1958 were completed. Completed hydroelectric plants at Liuchiahsia, Yenkuochia, Chingtunghsia, Tanchiangkou, Hsinfengchiang, and Hsinanchiang have raised the nation's total capacity considerably, although by 1975 only 5 percent of the country's hydropower potential was being exploited.

Shortages of electricity led to severe restrictions both on domestic and industrial electricity usage throughout the 1970s. Electrical codes limited rooms to one light bulb each, and factories frequently had to have scheduled shutdown periods to avoid overloading the grid.

The technologies used to generate electricity in China have come from a variety of sources inside and outside the country. The Chinese electrical manufacturing industry remained small through the late 1950s. Only through the transfer of Soviet and European technology could new power generation and distribution projects be undertaken. Still, the Chinese persevered to design their own versions of foreign technologies and improve upon them. By the 1960s, the Chinese had not only caught up but were innovators in generator and electric motor engineering. Chinese engineers, for example, innovated a water-cooled design in place of the standard gas cooling for turbines.

Another area in which the Chinese have excelled is so-called intermediate-scale energy technology, which combines a labor-intensive, traditional approach to construction, local materials and skill, and minimal capital investment. Official encouragement of this approach has led to the exploitation of small coal mines in rural areas, small hydropower stations, solar energy, and biogas technology. By 1975, there were over 60,000 small and medium (i.e., less than 1000 kW) hydroelectric facilities and several remarkable tidal power stations. The latter use special horizontal turbines and can operate with extremely low "heads" on the order of just a few inches.

The production of electricity rose very rapidly after about 1970, from under 100 billion kWh to over 650 billion kWh by 1990, doubling during the 1980s alone. A significant part of China's energy came from some 25 nuclear power plants. But household electrification was still limited, and industry used between 75 and 80 percent of the total electric output compared to around 35 percent in the United States. Much residential heat and light in smaller towns and on farms comes directly from oil lamps and coal or wood furnaces, and only 42 percent of urban households own, for example, an electric refrigerator. Electric service in China is still much less extensive than it is in the West, but the Chinese are finding their own path to electrification.

Ziao-lin Xi and M. Granger Morgan, "Energizing China: First Itself, Next the World," *IEEE Spectrum* 26 (March 1989): 59-63; Mark D. Levine et al., "China's Energy System: Historical Evaluation, Current Issues, and Prospects," *Annual Review of Energy and the Environment* 17 (1992): 412, 416; T. J. Wilbans, "Implementing Environmentally Sound Power Sector Strategies in Developing Countries," *Annual Review of Energy* 15 (1990): 256-261.

tions, elevating the wealthy and grinding the poor further down. Because electricity customers in India were required to pay part of the cost, the richest people in local villages got electricity first. There was evidence that poorer families, attempting to emulate the wealthy, would sacrifice large portions of their available cash resources in order to get electric service and run electrical appliances, making electricity a greater hardship for them.⁶⁰

The benefits of electricity in less developed countries were much easier to identify in the cities, where the economic barriers to electrification were lower. City dwellers live in close enough proximity that the investment necessary to extend lines to homes is lower than in rural areas where the population is dispersed. In Bangkok, Thailand, for example, the first electric power plant was actually built in 1890, but electricity served only wealthy households for the next sixty years. Nevertheless, international aid gradually helped Thailand electrify its largest cities, though the results did not become clear until the 1980s. One index of the use of electricity in Bangkok was the market penetration of electric refrigerators in households, which was only about 26 percent in 1976. By 1984, after a decade of rapid infrastructure building, it had risen to 62 percent.⁶¹

In several countries, particularly in Africa, large electric generating and transmission projects sometimes took on disturbing political overtones. Electrification in South Africa, for example, has reflected that country's history of extreme political and social inequalities between black and white citizens. Large electric

Case Study of Electrification II: Kenya

The story of electrification in Kenya illustrates some of the ways developing countries have been subject to the vagaries of Western theories about economic development. Some of these countries have become directly or indirectly dependent on the United States and Europe for their electric service. Kenya had virtually no electric power before 1945, but built up a significant central station generating capacity after that time using foreign technology and funding. Most electricity in the country today is generated by falling water or by burning fossil fuels, and there is one 45 MW geothermal plant as well. By 1986, the nationalized power industry reported 2206 gWh in sales, but noted that 59 percent of total supply was used by commercial enterprises in Nairobi and Mombassa.

Kenya's attempts to provide household electricity have had mixed results. In 1973, Kenya instituted an ambitious rural electrification program with Western assistance. But the program, underwritten indirectly by the Swedish government, was aimed mostly at electrifying rural industries rather than homes, and often electricity was used to replace existing power sources such as diesel engines, rather than being offered to new users. The high cost of extending lines from central stations to rural customers retarded the growth of the network. By the late 1980s, the only significant residential use of electricity was for heating water, but owners of domestic water heaters were only allowed to use electricity in off-peak hours. Consumer usage was controlled by the power plant operators, who switched on and off power to the villages using a technique euphemistically known as "ripple control." As Western aid agencies in the 1980s dislodged the idea that central stations were the single best way to provide electricity to homes, rural electrification at last began to succeed. Between 1987 and 1990, almost 10,000 homes were electrified using free-standing power plants based on small solar panels. While ordinary Kenyans now have better access to electricity, the country still depends on the West for engineering skill, equipment, replacement parts, and new technologies. Electrification has arguably changed the standard of living for some Kenyans; it has not resulted in economic development that is likely to persist if aid is cut off.

Hjort, Anders, *Socio-economic Effects of Rural Electrification: An Interim Report* (Institute for Development Studies, University of Nairobi, Nairobi, Kenya; 1974); Walubengo, Dominic, *Energy Systems in Kenya: Focus on Rural Electrification*, (KENGO Regional Wood Energy Programme for Africa, Nairobi, Kenya; 1992), 27-29, 44.

power generating facilities were put in place during the first three decades of the 20th century, but were used almost exclusively to the benefit of whites, either to supply power to cities, to power electric trains, or to run machinery in coal, diamond, and other mines. Power facilities became the targets of political protest, and a mine-mouth station built in South Africa in the 1960s had to be built with an anti-sabotage design.⁶² The long-distance transmission of power also took on new political implications in developing countries. A high-voltage dc transmission line from a large, expensive hydroelectric site built with Western assistance in Mozambique, which supplied power to South African industry,

was put out of service for much of the 1980s as a protest measure, demonstrating the vulnerability of the centralized systems relying on long, high-capacity transmission lines in times of political unrest.⁶³

Sometimes, as in the case of Nigeria, Western central station generation and transmission technologies failed both for political reasons and because of the lack of skilled engineers and trained managers. While the country had received American-style generating and distribution facilities after 1945, by 1990 the system had fallen into disarray. Working on a model based loosely on the Tennessee Valley Authority, the Nigerian power administration supplied electricity to all customers at extremely low rates subsidized by the government. The theory was that commercial and residential customers would quickly adopt electric service and gradually increase their power usage, as they had done in the United States. Unfortunately, the Nigerians were less successful than the TVA had been in stimulating high levels of household or industrial consumption. Since government subsidies became a permanent fixture, the government-owned power provider became locked into the position of providing electricity at low levels of efficiency (and thus at a high cost), but had no way to pass on costs to customers.

However, because the Nigerian Power Administration was expected to pay its own expenses, the perennial shortfall made it impossible to expand or even maintain the grid, so that after a while few new residential customers were being added. That meant that industry became the chief beneficiary of the low-cost, subsidized power. As a result, most Nigerian households simply did without electricity. Further, because of the neglect of maintenance and general lack of money, technical problems with the system became chronic. Blackouts occurred regularly, and power availability dropped as low as 50 percent. An estimated 30 percent of the energy actually generated was lost through inefficient operation. Trained employees were difficult to retain because they were so poorly paid, owing to inadequate sales of underpriced energy. In the end, blackouts forced industrial customers to install their own backup generating facilities, demonstrating their lack of confidence in the public utility but also highlighting the failure of subsidization as a long-term policy, because the small generators that they operated provided energy at a higher rate than they would

have paid if the government electricity was not subsidized. They were, in other words, prepared to pay more for their electricity than they were currently paying the government. In Nigeria, the transfer of this Western technological system had failed to take root in a non-Western culture and economy.⁶⁴

3. FAILURES IN RURAL HOUSEHOLD ELECTRIFICATION

While many other industrial and urban electrification projects around the world succeeded, by the late 1970s many rural electrification programs in developing countries were falling into disrepute. In too many countries, large power plants served mainly industrial consumers rather than households, and the plight of farm families was symbolized by the long-distance transmission lines that cut through the landscape, carrying electricity that was all but inaccessible to the majority of people. The theory that building an electric power “infrastructure” would lead to rapid modernization was proving to be untrue.⁶⁵

Blame for the apparent failure of Third World rural electrification through the end of the 1970s was placed primarily on governments, local elites, or international aid agencies and not on the engineers who conceived the technology. Most critics still believed that electric service based on the Western model was the best way to provide electricity anywhere in the world. But in the 1980s and 1990s those opinions changed. As one expert put it,

The orthodox approach of central station generation, which is ideal for industrialized countries and urban centers, may not make sense for rural areas, where the demand per consumer is only a small fraction of a kilowatt.⁶⁶

As late as the early 1990s, a few high-income nations still generated more than half of the world's electricity, but two billion people had no electricity at all.⁶⁷

Chapter 3

From Energy Crisis to Environmental Crisis, the 1970s and 1980s

The steady growth in demand for electricity after 1945 kept engineers in the United States, Europe, and other industrialized countries busy for many years. Yet their goals and problems changed significantly beginning in the late 1960s, due to the changing economics of central station construction and operation and an unprecedented movement to reduce pollution and conserve fuel. Utilities, after years of struggling to build new plants fast enough to keep up with the growth in demand, were unprepared for new environmental regulations, imposed by many governments in response to concerns about air pollution. Compounding this new problem was a sudden rise in the inflation rate (which made plant-building more expensive), the realization that nuclear power would be much more expensive than anticipated, and periodic rises in the price of the petroleum used to operate many conventional boilers.

Utility companies watched inflation swell and economic growth slow during the 1970s, as the price of the labor and resources used to operate a steam-powered generating facility ballooned 120 percent over the course of the decade.⁶⁸ The price of oil shot up during the Embargo of 1973 and the Iranian Revolution of 1979, so that the 1979 price of oil was over 400 percent greater than the 1969 price.⁶⁹ This was especially important since many power providers (especially in the United States) had begun a shift from coal to petroleum in order to meet the environmental regulations imposed in the late 1960s. But the most dramatic and unexpected turnaround for the industry, one that had both economic and environmental aspects, was the movement away from nuclear power, for years seen as the best answer to the world's future energy needs. By the 1970s, nuclear power had become part of a global controversy that pitted "experts" against the

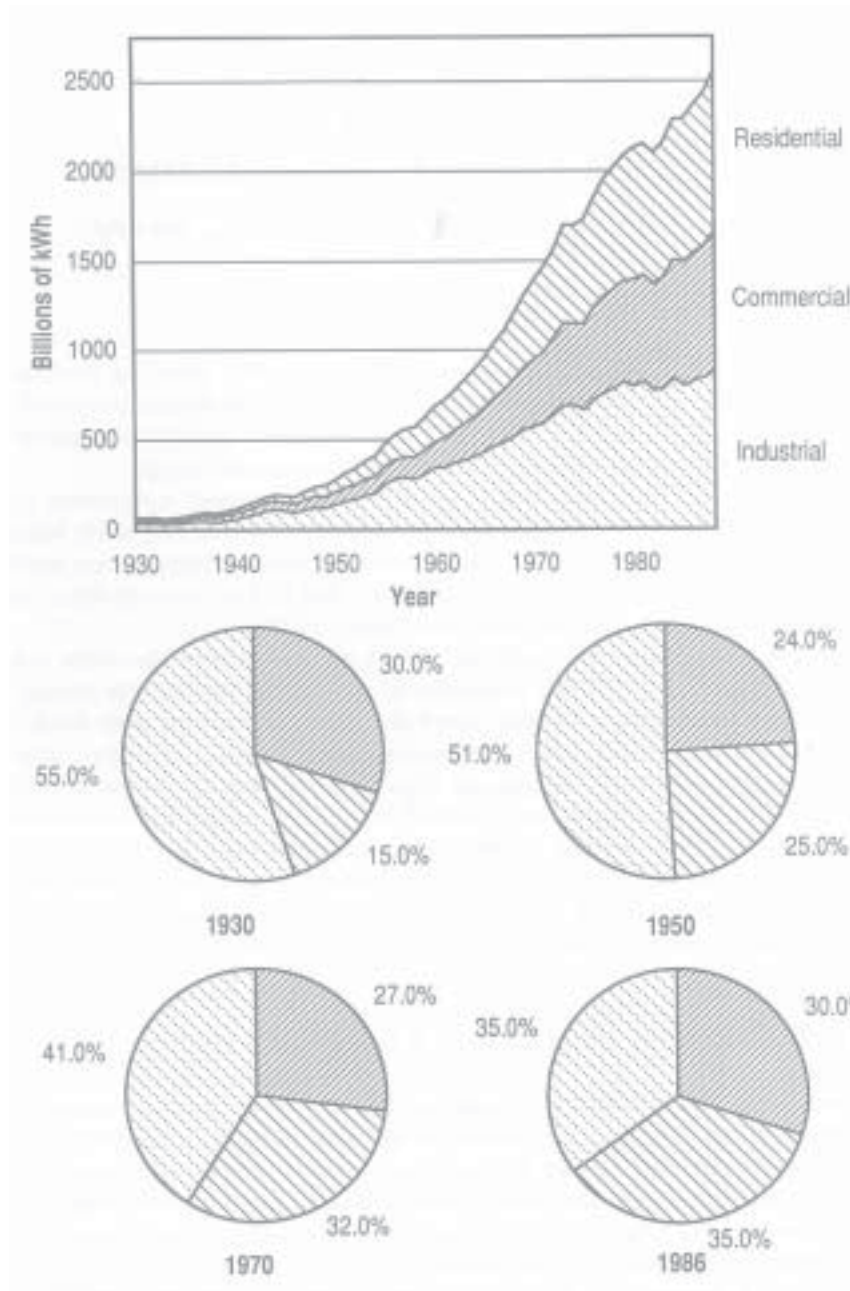


Figure 13. Sales of electric power in the United States, 1930-1986. Note the growth in residential use between 1930 and 1950.

public and engineer against engineer. The story of nuclear energy and its relationship to electrical engineering is worth reviewing in some detail.

1. NUCLEAR POWER TECHNOLOGIES REVISITED

Even in the heady days of the 1950s, problems with nuclear power were beginning to arise. For one, early nuclear technologies were developed in a sort of hothouse that was insulated from commercial realities. When these technologies were transferred to civilian power sectors, they could not compete economically with conventional power sources. However, the equipment manufacturers and utilities believed that additional experience would bring decreases in cost.

The industry suffered a serious setback in the United States after new licensing regulations were imposed following the 1969 Environmental Protection Act. A 1971 Federal Court ruling on environmental impact questions affected 103 plants in the United States in operation or under construction. Industry experts protested that nuclear power was being “regulated out of existence” and that the costs of building and operating a plant were unnecessarily high owing to extraordinary Federal and state rules.⁷⁰ In the United States, the building of new nuclear plants practically halted in the 1970s, while in Europe plant building continued, despite grave misgivings among politicians and the general public.

In Sweden, for example, where an extensive nuclear program was inaugurated in the 1960s, public opinion alternately supported and turned against the new energy source. The Swedish government called for a moratorium on new plant construction in 1973, but later permitted the building of 13 new plants through 1985. In many ways, the Swedish nuclear program was typical of several Western nations, in which an otherwise technical issue was transformed into an ongoing and central political issue.⁷¹

One of the main sources of opposition to nuclear power was based on the assumption that it was inherently unsafe. Many engineers argued that the plants were safe, and that built-in safety features could prevent and had prevented accidents. The possibility of accidents caused mainly by operator errors had been repeatedly suggested even before the incident at the Three Mile Island nuclear facility in Pennsylvania in 1979. The failure of several systems at Three Mile

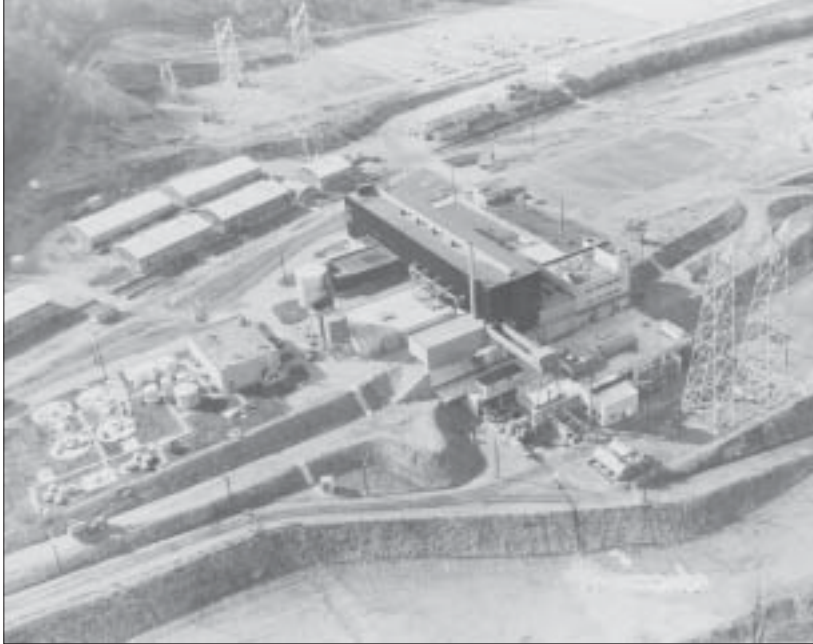


Figure 14. The Shippingport nuclear power plant lacks the distinctively shaped cooling towers familiar to many Americans, particularly after the extensive press coverage of the Three Mile Island accident.

Island, combined with human error, contributed to a partial meltdown of the nuclear reactor “core” and the escape of radiation into the atmosphere. Three Mile Island was less an environmental than a public relations disaster, for popular resistance to nuclear power was instantly catalyzed and the event marked yet another reappraisal of nuclear power in the United States. Compounding the problem was the coincidental release of the Hollywood motion picture “The China Syndrome,” which portrayed a “meltdown” at an American nuclear power plant.

Even more disastrous for nuclear power proponents worldwide was the massive environmental disaster brought about in 1986 by the explosive failure of a nuclear reactor at Chernobyl in the Soviet Union. In this case there were numerous deaths and the ultimate environmental consequences still cannot be accurately predicted. Supporters of nuclear power were quick to point out that the Russian reactor was of an inferior design, but the damage to the nuclear power industry had been done. The United States government demanded

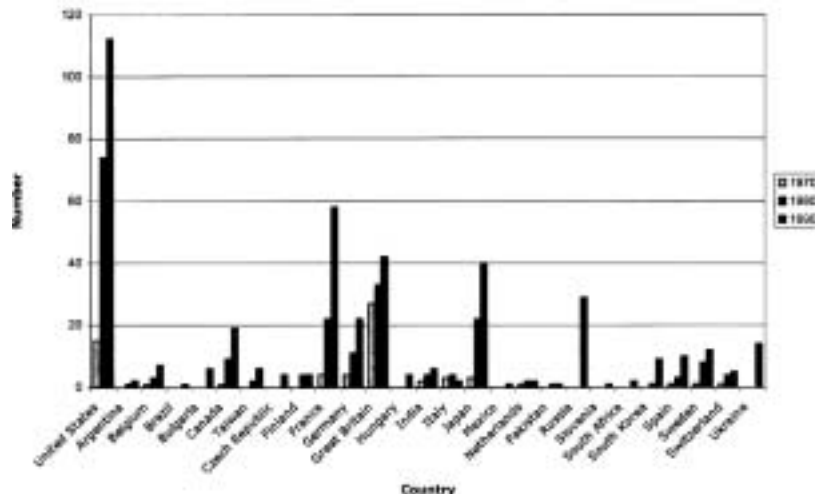


Figure 15. Number of nuclear reactors in use, 1970, 1980, 1990.

changes in the regulatory structure and operating procedures, which raised the cost of nuclear power generation virtually beyond the point of economic viability.⁷²

Nonetheless, the contribution to the total energy picture made by nuclear power was impressive. The most rapid growth came during the 1980s, when the fruits of projects begun in the 1970s began to be apparent. In the United States, nuclear-generated energy constituted less than 2 percent of all electricity generated in 1970, rising to about 12 percent in 1982 and then reaching a peak of approximately 21 percent in 1993.⁷³ But even in countries such as France and Belgium, where the share of nuclear power was much higher by the 1980s, nuclear power was increasingly seen as a “necessary evil to be tolerated, at least for a few decades, because of huge capital investments” and lack of alternatives.⁷⁴

In the meantime, new types of nuclear energy technologies appeared on the horizon. One of the most interesting is fusion power, a technology which has presented daunting technical problems. Fusion power’s proponents argued that the energy released from controlled nuclear fusion represented an unlimited source of power, because it did not depend on a scarce fuel. After years of government sponsorship in several different countries, fusion reactors have only recently reached the state at which they produce more power than they consume. Commercialization seems to be many decades in the future.⁷⁵

Nuclear Fusion Technology

Physicists and engineers have promoted the idea of nuclear fusion as an energy source for over half a century. Experimenters such as Andrei Sakharov in the Soviet Union reported promising results in controlled fusion reactions beginning in the late 1940s, and by the early 1950s there were several projects underway to build a commercially viable fusion reactor. More immediate results, however, came from the field of atomic weapons, where the first fusion bombs were tested in 1952 and 1953 by the United States and the Soviet Union. While progress toward a reactor continued during the 1960s and 1970s, it was not until 1986 that the next major breakthrough occurred. In that year, shortly after the fission-powered Russian reactor at Chernobyl suffered a major failure, the Nova reactor at Lawrence Livermore laboratories successfully created a fusion reaction using high-power lasers. Although the latest devices are now capable of significant fusion reactions, they have yet to generate the first watt of commercial electricity after nearly a half-century of development. The costs have been astronomical. The Tokamak Fusion Test Reactor, an experimental machine built at Princeton University, cost approximately \$228 million, and the organization to run it had an annual budget of \$28 million in 1997. Despite the slow progress and high cost, it would be an understatement to say that fusion is still a promising source of energy, but in recent years the political will to finish the project has begun to deteriorate. In the late 1990s, a new international development project was underway called the International Thermonuclear Experimental Reactor (ITER), but it was unclear whether it would at last succeed in producing the long-sought practical fusion device.

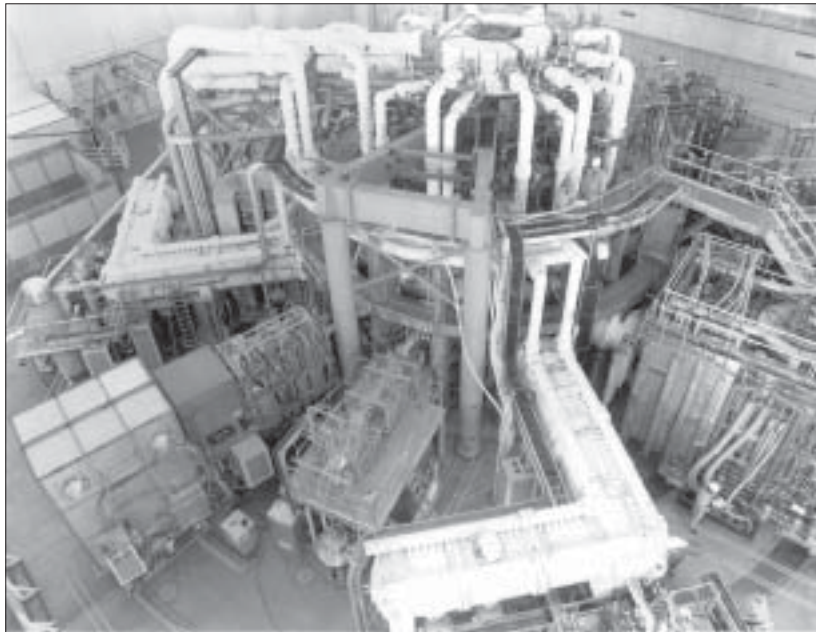


Figure 16. The Tokamak reactor at Princeton, New Jersey. Despite decades of research, commercial fusion power remains beyond engineers' grasp.

Since the mid-1980s, American companies with an interest in nuclear power technology have collaboratively developed a new type of reactor which is expected to overcome public objections. This Advanced Light Water Reactor (ALWR) is intended to be simpler and safer than existing designs. Similar efforts have emerged in Europe from two international collaborative organizations. However, it remains to be seen whether this reactor can be economically operated, whether it will survive government regulations, and whether the public will again accept the expansion of nuclear power.⁷⁶

2. THE DEVELOPMENT OF ALTERNATIVE ENERGY SOURCES

Nuclear power remained the only widely utilized, radically new generating technology from 1945 through the 1960s, but many other new sources of electricity waited in the wings. The Cold War and the resulting peacetime buildup of military might indirectly spawned not only nuclear energy, but also all sorts of energy-related research projects. Especially important in the long term were smaller-scale generating technologies, such as the solar panels used to provide power to satellites and other small pieces of electronic equipment.

But it was the oil crisis that brought several formerly military- or space-related energy technologies into the public light and made energy research part of the agenda of national governments worldwide. The year 1973, which saw a dramatic but short-lived jump in oil prices, marked a real turning point for electric power technologies. In protest of Western support for Israel, the Arab-dominated Organization of Petroleum Exporting Countries [OPEC] initiated an embargo on sales of oil to the United States and a 10 percent overall cut in production. The immediate result was long lines at gas pumps, high heating bills, and a worldwide economic downturn.

Many power utilities had acted in the postwar period as promoters of increased electric usage among consumers, through publicity campaigns and the direct sale of electric appliances. One of the most memorable images of this era was Reddy Kilowatt, the cartoon mascot of the power industry who reminded customers of the benefits of increased electricity usage. Now Reddy Kilowatt was replaced by a conservation campaign. Industry groups sponsored conservation messages on television, and across the United States utility companies placed stickers on customers' wall switches, reminding them to turn off the lights.⁷⁷

On the production side, there were widespread calls for greater efficiency and the development of new fuel sources, including a return to coal, which had fallen out of favor as a boiler fuel by 1945. The idea of “co-generation,” which had been employed in some countries for decades, was revived in the United States as a conservation measure. Co-generation was simply the use of waste heat from industrial processes to run conventional generators. Similarly, some industries began burning waste products (such as wood chips in paper manufacturing) to generate electricity locally.⁷⁸ There were many calls for such conservation measures, one of the most notable being economist Amory Lovins’ suggestion that the world’s energy needs could be met using some small fraction of the current fuel consumption through greater efficiency.

The fuel, environmental, and regulatory crises that power utilities in the United States and Western European countries experienced were not without their counterparts in other nations. In Russia and China, for example, fluctuations in fuel prices and the world economy drastically affected electrification programs. Where nuclear power seemed to be a key to future power production, it soon became evident that economical operation of nuclear plants remained problematical. Developing countries experienced economy-wide setbacks during the oil crises, which retarded the growth of electric power industries.

Western governments in the 1970s began pouring money into research and development efforts aimed at improving alternative energy sources and ending dependency on foreign oil. These programs experienced periodic cutbacks, and some were failures, but several resulted in technologies which are now widely used.⁷⁹ In the United States in 1973, under the threat of a federally created energy research institute to be funded by a utility tax, the electrical utility industry itself organized the Electric Power Research Institute. EPRI’s original mission was “to do all the advanced technology work on future energy sources and system components. The utilities felt they could deal with the everyday problems.”⁸⁰ Since that time, the organization has reversed its policy, focusing much less on developing future energy technologies and shifting to the invention of improvements to existing commercial equipment. EPRI owns a number of patented inventions and processes, for example, which the organization licenses to manufacturers for a fee. Events like the Three Mile Island nuclear accident also spurred EPRI to increase its activities in safety research.⁸¹

New, industry-wide research initiatives began much earlier in Great Britain. The Herbert Report of 1956 recommended increased emphasis on research in areas other than high-voltage transmission, which was already being studied. The British Central Electric Authority subsequently funded significant projects in fields such as magneto-hydrodynamics and cryogenics. Later, the organization switched most of its efforts to solving particular plant problems in a manner similar to the EPRI.⁸²

In addition to creating new organizational structures which allowed room for new technologies, utility companies and energy ministries redoubled their investigation of new technologies themselves. Many proposals for new types of generating technologies appeared, and almost all got serious consideration. Some were modifications of existing technologies, including fast breeder nuclear reactors, solar energy, and wind power. Others were more radical departures. For example, engineers in the Soviet Union quickly took the lead in the development of a magnetohydrodynamic [MHD] generator. In this system, a flow of conductive liquid or gas interacts with strong magnetic fields to generate electricity. While American researchers later took this idea up, it has not resulted in a commercial product.⁸³

Another interesting proposal was the use of storage batteries to “bottle” excess electricity generated during off-peak hours for use during periods of heavier load. Late 19th century dc power systems in the United States and Europe had sometimes used storage batteries for such purposes, but this system did not work with ac power. Battery storage survived in specialized applications, however. Telephone systems use battery storage to provide an extremely reliable source of energy to run telecommunications networks worldwide. The improvement of electronic ac-dc converters after 1945 revived interest in storage batteries, and one line of inquiry investigated the use of a new type of lithium-sulfur cell for this purpose. In the United States and Western Europe, this was done through government/industry consortia, or by private industry with considerable government subsidization. One such project was a storage battery/conversion facility built in Hillsborough, New Jersey in 1977 by the Public Service Electricity and Gas Company. Again, however, such research has not led to commercial success.⁸⁴

3. FUEL CELLS

The fuel cell is one example of a government-sponsored technology which has, after several decades of research and development effort, produced a viable technology. The fuel cell is a chemical method of producing electricity, somewhat analogous to an ordinary battery. The difference is that the fuel cell must be continuously

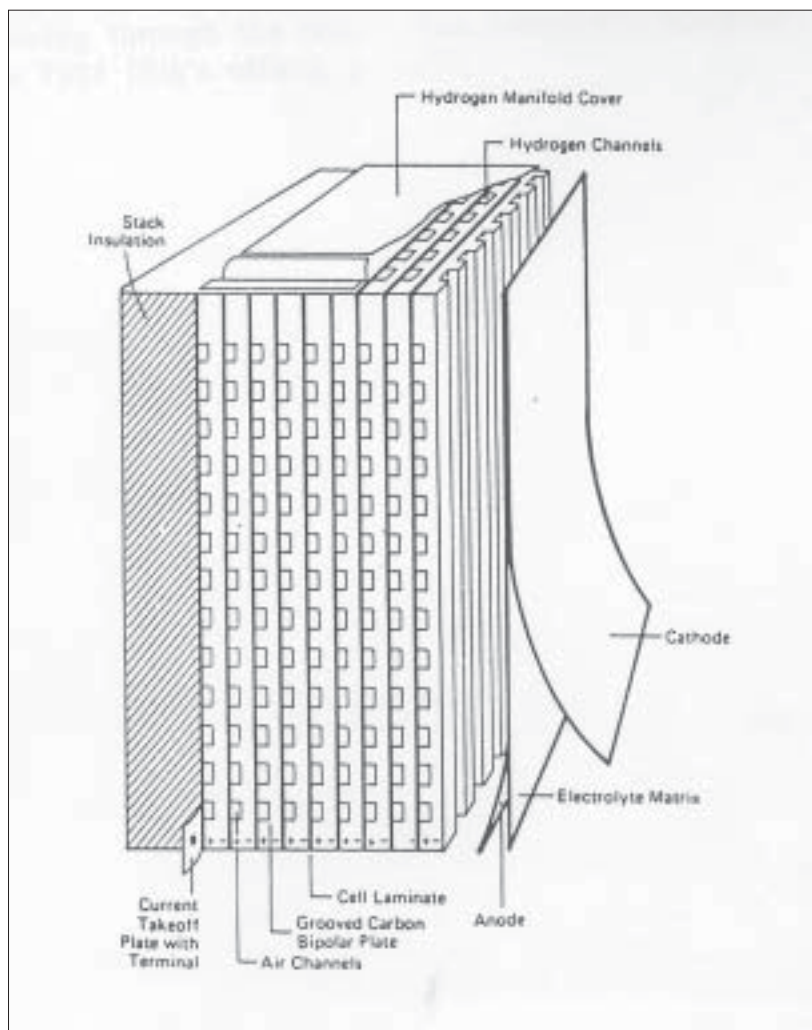


Figure 17. The essence of a fuel cell, such as the one above, is the chemical decomposition of hydrogen flowing through the cell.

supplied with chemical reagents in order to function. It does not hold a charge like a battery. The fuel cell derives current from a chemical reaction using oxygen from air and hydrogen from a fuel source (usually petroleum, synthetic fuels derived from coal, or natural gas, but renewable fuels such as methanol have been tried). In operation, fuel cells are silent and produce only water and carbon dioxide as waste products. The electrochemical process used in a fuel cell was discovered in the early 19th century, although it was not proposed for commercial purposes until the 1930s. In the 1950s, Westinghouse Electric developed commercial versions of these devices, but found only niche markets for them.

In the 1960s, fuel cells designed for NASA provided power for the Apollo spacecraft. Early NASA fuel cells supplied by General Electric Company used an unusual electrolyte composed of a polymer material in the form of a membrane. The resulting fuel cells were quite expensive. By the 1990s, fuel cells using less expensive materials and solid fuels were available and put into operation experimentally as part of utility company power networks. In the United States and Japan, where much of this research took place, government spending and industry consortia were crucial. The U.S. Federal government spent about \$140 million between 1991 and 1993 on fuel cell research.⁸⁵ Unfortunately, the U.S. Department of Energy has had difficulty transferring the financial responsibility for commercializing this technology to the private sector. Additionally, many utilities remain unconvinced that fuel cells represent an economical alternative to other medium-scale power sources, especially gas turbines.⁸⁶

4. SOLAR POWER

The history of solar energy conversion is another example of a technology that is inextricably linked to government policy and financial support. In the United States, small light-sensitive devices were developed privately and used extensively as sensors in various types of equipment from the 1930s. While solar cells were developed by the 1950s which could generate enough electricity directly from sunlight to operate electronic circuits, the amount of current was small and the price was high.

Nonetheless, solar cells found niche applications by the 1960s. The most famous application was in space: from the 1960s on, many satellites were powered by solar cells. These solar-power applications were little-noticed by the public unless they failed, as was the case in 1974 when the solar panels on NASA's Skylab failed to deploy and had



Figure 18. Used for many years mainly for unusual applications such as space flight or rural telephony, solar cell research was revived in the 1970s for use in the power grid.

to be repaired in space. A second important application was developed by telephone companies to operate remote repeaters and other equipment. Solar cells remained inefficient and expensive compared to other methods, and were suitable only where no other energy source could be used or where cost was not a major consideration.⁸⁷

Solar power for utility applications was given a temporary boost through the government funding of applied research on solar cells and the construction of experimental solar stations. Not all of these solar stations used solar cells; several large systems used computer-controlled, movable mirrors to focus light on a boiler, which produced steam to drive a turbine. However, these large-scale plants remained experimental, and funding eventually dried up.

Perhaps more notable was the continued development of photoelectric solar cells during the 1970s and 1980s. Large sums of federal and private money were expended on this technology, the government allocation amounting to about \$3 billion during the 1970s alone. In the United States, much of the research and development undertaken by equipment manufacturers, utilities, and organizations like EPRI focused on the needs of utilities. But even before the technology neared the “breakeven point” established by the utilities to describe the point at which it could compete economically with thermal plants for bulk power generation, private companies in Europe and the United States were using this technology in new ways.⁸⁸

As criticism among policy-makers of the “grid paradigm” for rural electrification in underdeveloped countries reached a peak, new ideas about small-scale, non-networked, renewable generation began to look more attractive. In some remote places where the costs of building and maintaining power lines could amount to 80 to 90 percent of the operating costs of a utility, small solar panels could be used instead. As early as 1960, a technical assistance project in Chile used solar panels to operate electric machinery. By the early 1990s, several companies had great success selling solar power systems for use in India, Africa, and elsewhere. The most popular product was a 50 W solar panel that could be used to keep a small battery charged.⁸⁹ By 1994, there were about 62,000 of these stand-alone solar power systems in use in India alone. About 29,000 of these were used for lighting, water pumping, and domestic use.⁹⁰ One indication of the transfer of solar cell technology from Western to non-Western nations can be seen in export data. In the mid-1990s, nearly 75 percent of the solar panels manufactured in the United States were exported.⁹¹

More recently, attention in the United States and Europe has turned to increasing the efficiency of solar cells further, and developing techniques to mass produce them. While the generation of crystalline silicon cells being sold in the 1980s reached 10 to 14 percent conversion efficiency, the new technology of vacuum deposition of a thin film of semiconducting material on a glass substrate offered a lower-cost, higher-efficiency alternative.⁹²



Figure 19. A solar power unit developed by the Jet Propulsion Laboratory to drive a Stirling engine, 1982.

5. WIND POWER

By far the most successful alternative energy technology has been the exploitation of wind. While the overall trend in solar power has been from unsuccessful centralized applications to commercially successful decentralized applications, such has not been the case for wind generation. This form of small- to medium-scale generation was repeatedly passed over by American utility companies before the 1970s because it was considered unreliable and unsuitable for large-scale exploitation. But in time, due to changes both in the technology and in the business environment, wind power became a part of established electrical networks.

The use of wind energy to serve various industrial purposes is quite old, dating at least to the 12th century in Europe.⁹³ Unlike other power sources such as water or steam, wind power was for the most part left behind in the late 19th century by electric companies looking for ways to drive generators. It was seen as unreliable and unavailable

in sufficient quantities to power larger machines. Wind power development continued in Scandinavia, in particular in directly driving machines, but also for electric generation. By the time of World War II, there were also about 10,000 electric generators driven by wind in the Soviet Union, ranging in power capacity from 1 to 15 kW. The world's largest wind-powered generator in operation in 1990 was a product of Soviet engineering located in the Crimea.⁹⁴

Historically, the windmill has been associated with Holland, where large mills dating from medieval times are preserved as cultural icons. Several Dutch firms were especially active in the development of wind generators, and by World War II, the Dutch grid was being substantially supplemented by wind-generated electricity.⁹⁵ Danish engineers in 1957 built a 200 kW wind-powered "Gedser" generator, which operated continuously for a decade. The energy crisis of the early 1970s revived interest in wind-powered electric generation, and a number of European firms quickly moved to the forefront in providing updated versions of this ancient technology. Early emphasis in America was on the development of multi-megawatt wind turbines, although such designs did not see much commercial success.⁹⁶

The turning point for alternative energy utilization in the United States, including wind power technology, was national legislation which in 1978 forced utilities to purchase the power generated by independent producers. This act, called the Public Utilities Regulatory Policies Act (PURPA), was intended to advance deregulation in the industry, but also to encourage experimentation with new energy technologies. A wave of windmill construction projects immediately followed the passage of PURPA.⁹⁷ Internationally, many power providers in Europe also denationalized (or, in the case of the United States, deregulated) their power industries during the 1980s, leading to the entrance of new competitors.

By the early 1980s, spurred by tax incentives, competition from private wind power utilities, and a new willingness to experiment with non-steam generating technologies, American utility companies also began installing experimental "wind farms," most notably at Altamont Pass in California. Here, the utilities installed wind turbines of smaller capacity (typically 17 to 600 kW) in clusters. Much of this development through the late 1980s was concentrated in California, but it spread in the 1990s to other parts of the country. The total number of wind turbines in commercial service in the United States grew from under 200 in 1981 to around 17,000 in 1989.⁹⁸ The technology of wind

turbines began to change very rapidly, especially in the use of electronic controls and the development of machines that could work efficiently at varying speeds instead of having to be kept at a constant speed. Here, as with many other new sources of energy, developments in power electronics proved crucial. Successful windmills typically used thyristors (the electronic components discussed in an earlier section) to regulate voltage levels and allow variable-speed operation, along with efficient, electronic ac-to-dc converters to allow easy connection to existing power grids.⁹⁹

When federal tax incentives in the United States expired in 1985, sales of new wind turbines dropped dramatically and many companies left the market. Despite the uncertain economics of wind energy, by the 1990s wind power was a fairly well established technology. It was at the forefront of what the utilities called “distributed generation” (DG). This new approach to power service incorporated ideas which had first been articulated at the very infancy of the industry. Now, through careful management, small generators (including wind power and solar collectors in some areas, gas turbines, and later fuel) would be placed at the customer premises or located in suitable areas. However, unlike the “autoproducers” of an earlier era, these facilities would be linked to the grid in case demand overloaded the local generator or it failed completely. The DG approach defers or eliminates the need to add large central plants, and appeals to managers who see only limited future growth in demand for electricity.¹⁰⁰

Thus, while solar energy technologies that were developed in response to the Western energy crisis contributed to the electrification of households in other parts of the world, other alternative energy technologies have made less of an impact. The model of distributed generation, however, may prove to be viable both in industrialized and developing areas, and as technologies such as fuel cells continue to develop, they may well see extensive use around the world.

Chapter 4

Conclusions

There is no denying the ubiquity of electrical technology in our culture. In the United States, utility companies procured almost 2,500 trillion kilowatts in 1985, the highest figure for any nation in the world. Electrically powered devices from light bulbs to personal computers permeated Western life after World War II, and the production and distribution of electricity grew to meet the demand. The unrelenting drive to produce more power had the effect of extending prewar techniques and stimulating new ones. Conventional fossil fuel turbogenerators got larger through the 1960s before apparently reaching the limits of their designs. The maximum practical transmission voltages increased to nearly double what they had been just a decade before World War II.

The postwar period also saw many areas of the world receiving electrical service for the first time. International development organizations, motivated both by philanthropic and political impulses, made rapid strides in building or updating electric grids in Central and South America, Asia, and Africa. Parts of the far-flung empires of China and the former Soviet Union were also electrified. Yet the availability and level of consumption of electricity has become one of the demarcations between rich and poor in our world. In stark contrast to the United States' 2,500 trillion kilowatts stand most of the other nations of the world—none of the top 125 electricity-producing nations in the world generate more than 50 billion kilowatt hours. None of the bottom 30 generate more than 1 billion kilowatt hours. This disparity between nations will continue to be a divisive force in world affairs.

Nations attempting to industrialize in the 21st century may not choose (or be able) to duplicate the model set by Western countries.

The inherently unsustainable use of fossil fuels, which has underpinned most electrical generation so far, probably cannot be continued for long in many developing nations, simply because they lack significant fuel resources. Furthermore, the well-established Western paradigm of centralized stations and bulk distribution may never be suitable for the rest of the world. The question is whether advanced Western technology of other sorts will continue to play a dominant role in non-Western development.

During and after the 1970s, engineers had to try harder than before to find entirely new sources of energy. Nuclear power was the technology that many engineers initially thought would best meet postwar needs. Through a monumental engineering effort, nuclear power became a reality, and by the 1990s it was supplying a sizable part of the world's energy requirements. Yet this technology was not without major drawbacks, and as the century draws to a close, nuclear power is in retreat.

In the West and in nations already well-served by electric power, it seems likely that large-scale, centralized technologies will continue to thrive. However, the economic and regulatory challenges faced by U.S. utilities in the 1980s encouraged the application of several decentralized technologies such as wind power and fuel cells, which might otherwise have remained experimental or under-utilized. These new technologies, along with conservation, are now widely accepted as an alternative to new plant-building. But as utilities supplement their central stations with these smaller-scale generating techniques, and as the system gets more complex, engineers face new problems of controlling the grid.

Today, the practical problems associated with operating a vast power grid have brought power engineers back to the same basic problem they faced in the early postwar years: reliability. How to balance the issues of reliability and system management with economics, conservation of resources, and the environment will be a major concern for 21st century engineers.

Notes

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