
From Shafts to Wires: Historical Perspective on Electrification
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From Shafts to Wires: Historical Perspective on Electrification

WARREN D. DEVINE, JR.

The shift from steam to electric power in manufacturing is recounted. Between 1880 and 1930 the production and distribution of mechanical power rapidly evolved from water and steam prime movers with shaft and belt drive systems to electric motors that drove individual machines. The use of electricity reduced the energy required to drive machinery, but more important, enabled industry to obtain greater output per unit of capital and labor input. Reduced energy needs and increased productivity in manufacturing influenced the relationship between energy consumption and gross national product in the first three decades of the twentieth century.

MAJOR changes took place between 1880 and 1930 in the forms of energy that were produced and used in the United States. These changes included switches from coal to oil and natural gas, and the shift from direct use of raw energy forms (coal and water power) to the use of processed energy forms (internal combustion fuel and electricity).

One reason these shifts were important was that natural gas, internal combustion fuel, and electricity could be used with greater thermal efficiency than the fuels they replaced. For the economy as a whole, the general trend was toward increased thermal efficiency in converting primary energy into heat and mechanical work, and this trend was more pronounced in the twentieth century than in the latter part of the nineteenth. This was true despite the fact that the generation of electricity—with large thermal losses—grew much more rapidly than total primary energy consumption. These increases in thermal efficiency

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are reflected by a general decline in energy consumption relative to gross national product (GNP) after World War I (Table 1 and Figure 1A).

Another reason that shifts to natural gas, internal combustion fuel, and electricity were important was that these forms of energy could be used with greater productive efficiency than coal and water power, producing more goods and services per unit of capital, labor, energy, and materials employed. Indeed, just as the trend in the ratio of energy consumption to GNP changed dramatically after World War I, so also did certain measures of productivity in the manufacturing sector. Output per man-hour increased at an average annual rate of 1.3 percent before 1919 and 3.1 percent after, while the downward trend in output per unit of capital input reversed direction (Table 2 and Figure 1B).

TABLE 1
ENERGY CONSUMPTION AND GROSS NATIONAL PRODUCT, 1890–1980

Year	*GNP (billion 1972 dollars)*	*Energy Consumption (quadrillion Btu)*	*Energy ÷ GNP (thousand Btu per 1972 dollar)*
1890	79.8	4.497	56.35
1895	94.8	5.355	56.49
1900	116.4	7.572	65.05
1905	145.8	11.369	77.98
1910	186.0	14.800	79.57
1915	193.6	16.076	83.04
1920	214.3	19.768	92.24
1925	276.0	20.878	75.64
1930	285.6	22.253	77.92
1935	260.0	19.059	73.30
1940	344.1	23.877	69.39
1945	560.4	31.439	56.10
1950	534.8	33.972	63.52
1955	657.5	39.729	60.42
1960	737.2	44.080	59.79
1965	929.3	52.990	57.02
1970	1085.6	66.830	61.56
1975	1233.9	70.707	57.30
1980	1480.7	76.201	51.46

Sources: GNP 1890–1905 is from U.S. Bureau of the Census, *Historical Statistics of the United States, Colonial Times to 1970, Bicentennial Edition, Part I* (Washington, D.C., 1975), Series F 1–5, converted from 1958 dollars to 1972 dollars using implicit price deflator 0.6604. GNP 1910–1975 is from U.S. Bureau of Economic Analysis, *The National Income and Product Accounts of the United States, 1929–1976, Statistical Tables*, A Supplement to the *Survey of Current Business* (Washington, D.C., Sept. 1981), Tables 1.2 and 1.22. GNP 1980 is from U.S. Bureau of Economic Analysis, Department of Commerce, *Survey of Current Business*, 61 (Dec. 1981). Energy consumption 1890–1955 is from Sam H. Schurr and Bruce C. Netschert, *Energy in the American Economy, 1850–1975* (Baltimore, 1960), Table 48, mineral fuels and hydropower. Energy consumption 1960–1970 is from U.S. Energy Information Administration, *1980 Annual Report to Congress, Volume Two: Data*, DOE/EIA-0173(80)/2 (Washington, D.C., 1981), Table 1. Energy Consumption 1975–1980 is from U.S. Energy Information Administration, *Monthly Energy Review*, DOE/EIA-0035(82/01), Jan. 1982.

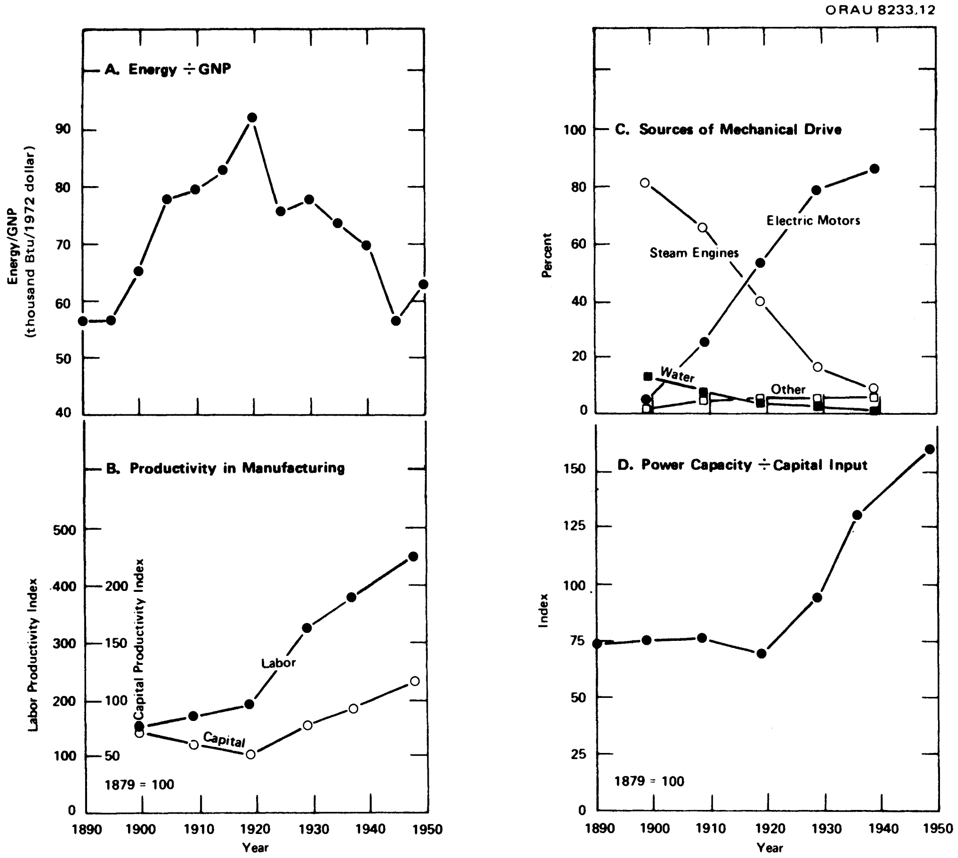

FIGURE 1
INDICATIONS OF CHANGE IN ENERGY USE

Source: Tables 1–4.

Perhaps the most rapid and complete transition in energy use was the shift from steam power to electric power for driving machinery. Steam power prevailed at the turn of the century, with steam engines providing around 80 percent of mechanical drive capacity. By 1920, electricity had replaced steam as the major source of motive power, and in 1929—just 45 years after their first use in a factory—electric motors represented about 78 percent of total capacity for driving machinery (Table 3 and Figure 1C).

Despite the dramatic shift in power sources between 1890 and 1920, total power capacity increased at almost the same rate as total capital in manufacturing. Then an equally dramatic change took place in the relation between power capacity and capital input. Beginning around 1920, power capacity increased much faster than capital input—a phenomenon that persisted through the 1940s (Table 4 and Figure 1D). It would not be unreasonable to expect this change in trend to be associated with an increase in the ratio of energy consumption to GNP; but as we have seen, just the opposite actually occurred.

In the following sections the shift to electricity in production is viewed in detail from the standpoint of engineers and entrepreneurs present at the time of the transition. These witnesses agreed that the substitution of electric power for steam power reduced the energy needed to drive machinery; more important, however, this substitution went hand in hand with improvements in factory organization, considerably enhancing output relative to input. The witnesses' observations are consistent with the post-World War I decline in the ratio of energy consumption to GNP (Figure 1A) and with increasing productivity in the manufacturing sector after 1920 (Figure 1B). Moreover, a detailed look at the evolution of power distribution in manufacturing helps explain the puzzling rise of power capacity relative to capital input in that sector (Figure 1D).

LINE SHAFT DRIVE

Until late in the nineteenth century, production machines were connected by a direct mechanical link to the power sources that drove them. In most factories, a single centrally located prime mover, such as a water wheel or steam engine, turned iron or steel "line shafts" via pulleys and leather belts. These line shafts—usually 3 inches in diameter—were suspended from the ceiling and extended the entire length of

TABLE 2
INDEXES OF INPUT, OUTPUT, AND
PRODUCTIVITY IN MANUFACTURING, 1879–1953
(1879 = 100)

	Input			*Productivity*	
Year	*Labor (1)*	*Capital (2)*	*Output (3)*	*Labor (4)*	*Capital (5)*
1879	100.0	100.0	100.0	100.0	100.0
1889	141.5	231.6	179.4	126.8	77.5
1899	184.4	385.5	269.6	146.2	69.9
1909	255.5	715.8	425.5	166.5	59.4
1919	320.4	1,222.4	598.0	186.6	48.9
1929	304.9	1,315.8	980.4	321.5	74.5
1937	269.5	1,123.7	1,012.7	375.8	90.1
1948	405.2	1,589.5	1,805.9	445.7	113.6
1953	452.7	2,022.4	2,386.3	527.1	118.0

Note: Column 1 is an index of total manhours in production and nonproduction. Column 2 is an index of real net capital stock multiplied by a baseyear rate of return on capital; net capital stock includes fixed capital valued at original cost less accumulated depreciation, and inventories. Column 3 is an index of total physical volume of output supplemented by deflated value of product. Column 4 is an index of output per manhour: Column 3 ÷ Column 1. Column 5 is an index of output per unit of capital input: Column 3 ÷ Column 2.
Source: John W. Kendrick, *Productivity Trends in the United States* (Princeton, 1961), Table D-1.

TABLE 3
SOURCES OF MECHANICAL DRIVE IN MANUFACTURING ESTABLISHMENTS, 1869–1939
(capacity in thousand horsepower)

	Direct Drive (Prime Movers)						
Year	*Steam Engines (1)*	*Steam Turbines (2)*	*Internal Combustion Engines (3)*	*Water Wheels and Turbines (4)*	*Total Direct Drive (5)*	*Indirect Drive (Primary and Secondary Electric Motors) (6)*	*Total Direct and Indirect Drive (7)*
1869	1,216	—	—	1,130	2,346	—	2,346
1879	2,186	—	—	1,225	3,411	—	3,411
1889	4,581	—	9	1,242	5,832	16	5,848
1899	8,022	—	120	1,236	9,378	475	9,853
1909	12,026	90	592	1,273	13,981	4,582	18,563
1919	11,491	465	856	970	13,782	15,612	29,394
1929	6,857	1,112	722	623	9,314	33,844	43,158
1939	4,216	1,736	866	394	7,228	44,827	52,055

Sources: Columns 1–4 are estimates based on Richard B. DuBoff, "Electric Power in American Manufacturing 1889–1958" (Ph.D. dissertation, University of Pennsylvania, 1964), pp. 66–69 and Tables 14 and E-6. Columns 5 and 6 are from DuBoff, Tables E-6 and 13, respectively. Column 7 is the sum of Columns 5 and 6.

TABLE 4
TOTAL MECHANICAL DRIVE POWER CAPACITY PER UNIT OF CAPITAL INPUT IN MANUFACTURING, 1879–1953

Year	*Total Mechanical Drive Power Capacity*		*Index of Capital Input*	*Index of Power Capacity per Unit of Capital Input*
	Thousand h.p.	*Index*		
1879	3,411	100.0	100.0	100.0
1889	5,848	171.4	231.6	74.0
1899	9,853	288.9	385.5	74.9
1909	18,563	544.2	715.8	76.0
1919	29,394	861,7	1,222.4	70.5
1929	43,158	1,265.3	1,315.8	96.2
1937	50,276	1,473,9	1,123.7	131.2
1948	86,095	2,524.0	1,589.7	158.8
1953	105,007	3,078.4	2,022.4	152.2

Sources: Horsepower 1879–1929 is from Table 3, Column 7; horsepower 1937, 1948, and 1953 are by linear interpolation using Table 3, Column 7 and a value for 1954 of 108,789,000 h.p. from the sources used in deriving Table 3. Capital input index is from Table 2, Column 2.

each floor of a factory, sometimes even continuing outside to deliver power to another building. Power was distributed between floors of large plants by belts running through holes in the ceiling; as these holes were paths for the spread of fire, interfloor belts were often enclosed in costly "belt towers." The line shafts turned, via pulleys and belts, "countershafts"—shorter ceiling-mounted shafts parallel to the line shafts. Production machinery was belted to the countershafts and was arranged, of necessity, in rows parallel to the line shafts. This "direct drive" system of distributing mechanical power is illustrated in Figure 2A.

The entire network of line shafts and countershafts rotated continuously—from the time the steam engine was started up in the morning until it was shut down at night—no matter how many machines were actually being used. If a line shaft or the steam engine broke down, production ceased in a whole room of machines or even in the entire factory until repairs were made.

To run any particular machine, the operator activated a clutch or shifted the belt from an idler pulley to a drive pulley using a lever attached to the countershaft. Multiple pulleys offered speed and power changes. Drip oilers, suspended above each shaft hanger, provided continuous lubrication. Machine operators were usually responsible for the daily filling and adjusting of these oilers and for periodically aligning the belts. As the belts stretched and became loose, they had to be shortened slightly and the ends laced tightly together. These maintenance tasks took significant amounts of time, as a large plant often contained thousands of feet of shafting and belts and thousands of drip oilers.

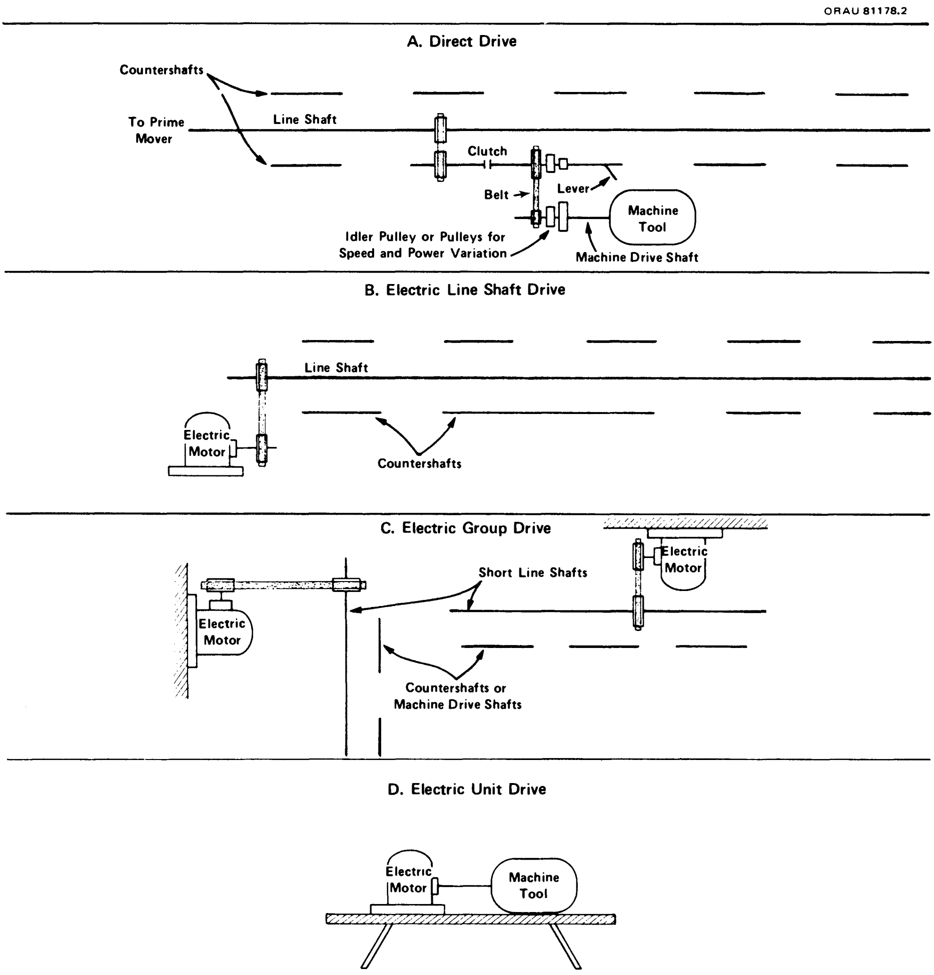

FIGURE 2
EVOLUTION OF POWER DISTRIBUTION IN MANUFACTURING

Source: See text.

Electricity was probably first used for driving machinery in manufacturing in 1883—the year after electric power was first marketed as a commodity by Thomas A. Edison.[1] (A chronology of the electrification of American industry is given in Figure 3.) Early electric motors operated on direct current—the only kind available from the Edison generating stations and the kind produced by incandescent-lighting generators owned by individual firms. Prior to 1885, direct current (d.c.) motors had usually less than one horsepower (h.p.) capacity, and were thus limited in application.

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[1] Charles Day, "Discussion on the Individual Operation of Machine Tools by Electric Motors," *Journal of the Franklin Institute*, 158 (Nov. 1904), 321.

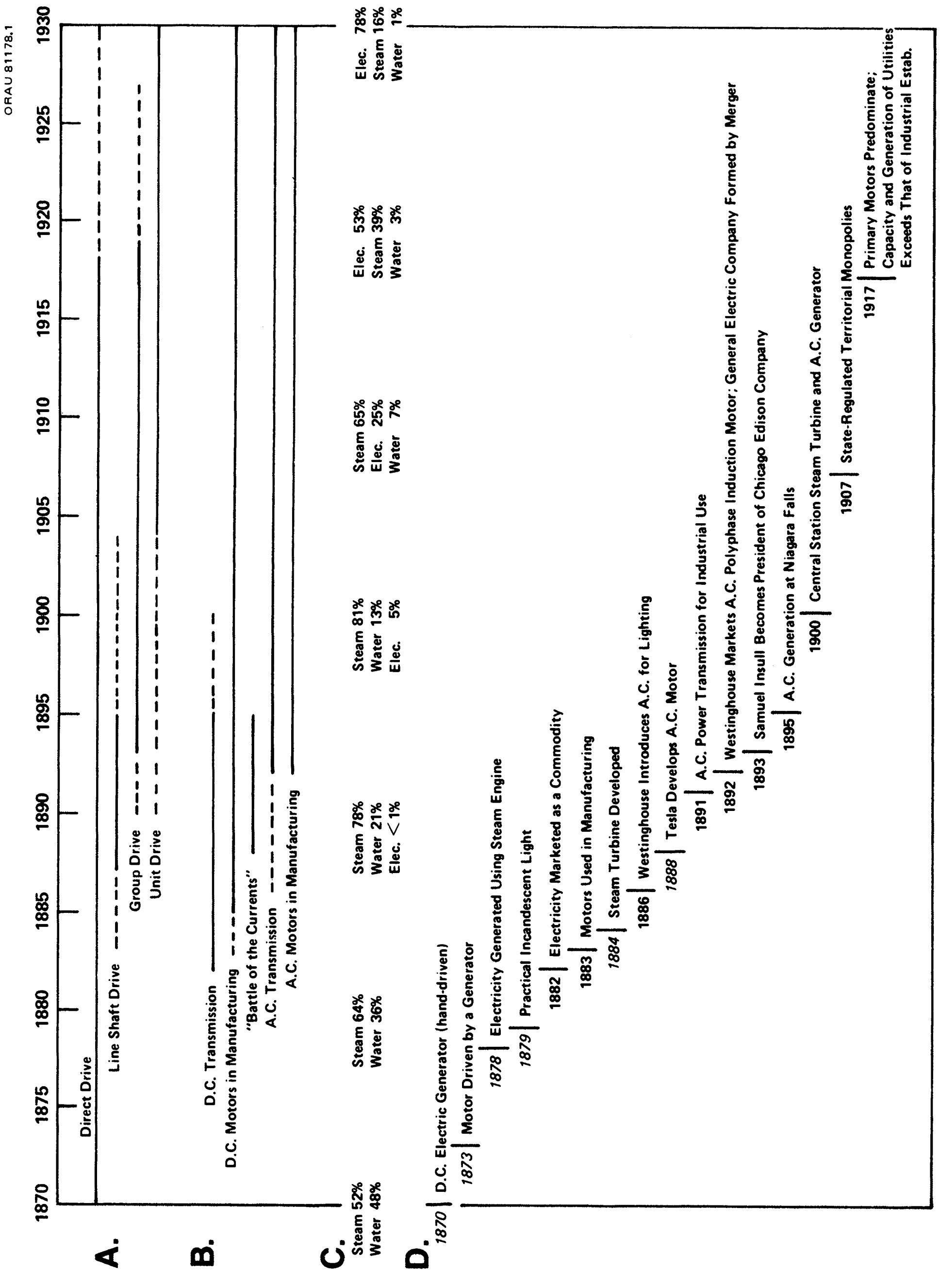

FIGURE 3

CHRONOLOGY OF ELECTRIFICATION OF INDUSTRY: (A) METHODS OF DRIVING MACHINERY; (B) RISE OF ALTERNATING CURRENT; (C) SHARE OF POWER FOR MECHANICAL DRIVE PROVIDED BY STEAM, WATER, ELECTRICITY; (D) KEY TECHNICAL AND ENTREPRENEURIAL DEVELOPMENTS

The first reliable and efficient d.c. motors in capacities exceeding one h.p. were developed by Frank Sprague, a former employee of Edison.[2] These motors, introduced in 1885, were designed for use on the Edison d.c. circuits. The Edison Electric Light Company encouraged the use of motors because daytime motor loads would complement nighttime illumination loads; since the marginal cost of serving these loads was relatively low, large profits were foreseen. By late 1886, 250 Sprague motors of 0.5 to 15 h.p. capacity were operating in a number of cities across the United States;[3] in 1889, total electric motor capacity in manufacturing exceeded 15,000 h.p., with over one-quarter of this capacity in printing and publishing establishments.[4]

By the early 1890s then, d.c. motors had become common in manufacturing, but were far from universal. Mechanical drive was first electrified in industries such as clothing and textile manufacturing and printing, where cleanliness, steady power and speed, and ease of control were critical.[5] But although electric motors may have improved the quality of work, they did not change the method of providing power to machinery on factory floors. As illustrated in Figures 2A and 2B, the only difference between direct drive and the earliest electric drive system was the type of machine used to turn the line shafts. In the first electric drive system—called "electric line shaft drive"—all countershafts, belts, pulleys, and clutches remained. Thus a single motor might have driven a few or several hundred machines; in textile mills it was not uncommon for large motors of several hundred h.p. capacity to drive well over one thousand looms.

The costs of turning line shafts with steam engines and with electric motors had been thoroughly examined by 1891. In a lecture delivered before the Franklin Institute, Dr. Louis Bell reported that when small amounts of power were needed, it was usualy cheaper to use electricity than steam.[6] This was so because small steam engines were much less energy efficient than large ones, and because the price of small amounts of direct current electricity could be low if generated in large quantities in a central station.

But in plants that used large amounts of power it continued to be cheaper to drive machinery with steam engines than with electric motors. As noted earlier, the large steam engines were relatively energy efficient, and large amounts of direct current electricity were expensive or simply not available from the young electric utilities. Nevertheless,

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[2] Harold C. Passer, *The Electrical Manufacturers, 1875–1900* (Cambridge, Massachusetts, 1953), pp. 238–40.

[3] "New York Notes," *Electrical World*, 9 (Feb. 12, 1887), 82.

[4] Richard B. DuBoff, "Electric Power in American Manufacturing 1889–1958" (Ph.D. dissertation, University of Pennsylvania, 1964), p. 228.

[5] "Fine Printing Done by Electric Power," *Electrical World*, 15 (1890), 432.

[6] Louis Bell, "Electricity as the Rival of Steam," *Electrical World*, 17 (Mar. 14, 1891), 212.

> The electric motor may be cheaper than steam even when the latter may be used on a large scale; the only condition being that we shall be able to take advantage of cheaper production [elsewhere] by the ability electricity gives us to transfer power from a distant point . . . we must look upon electricity as an enormously powerful and convenient means of transferring power from one point to another with the greatest simplicity and very small losses.[7]

This view of electricity as a means of power transmission was common in the early 1890s. It became apparent that large factories did not have to be located adjacent to sources of water power nor did they have to be designed about a large steam engine if it was particularly inconvenient to supply the engine with coal. Instead, power could be produced at good water power sites or coal depots some distance away and transmitted to the plant in the form of electricity.

A Columbia, South Carolina, textile mill built in 1893 had been located near water power, but mechanical transmission of power from the water wheels to the mill machinery proved impractical. Two electrical equipment manufacturers, Westinghouse and Siemens-Halske, proposed transmission systems that were in accord with the practice of the time: direct current would be generated at the river and transmitted across a canal to the mill, where large motors would turn the line shafts. In these proposals, electricity was simply a substitute for a thousand-foot cable power transmission system.[8]

In 1895, Professor F. B. Crocker of Columbia University visited Baltic and Taftville, Connecticut, "to see the practical working of the well-known power transmission plant between these places."[9] Both water and steam power had previously been used to run the Ponemah textile mill at Taftville. A hydroelectric plant was then installed at a dam upriver at Baltic. The power was transmitted via overhead lines to Taftville, where "motors are located in the basement of the mill, near the engines which they replace. They are belted to pulleys which are connected to their respective shafts by friction clutches . . . one of these motors drives 1,200 looms requiring an expenditure of about 155 horsepower. The other drives 500 looms."[10]

In both the above examples, electric power was preferred because it enabled distant, low-cost mechanical power to be transmitted to the mills relatively easily. The means of distributing power within the plants, however, remained unchanged. Steam engines and water wheels were simply replaced by electric motors, and these motors drove line shafts via belts and pulleys. Electricity was seen as a way to transmit mechanical power to factories, but not yet as an agent for distributing

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[7] Ibid.

[8] Passer, *Electrical Manufacturers*, pp. 303–05.

[9] F. B. Crocker, V. M. Benedikt, and A. F. Ormsbee, "Electric Power in Factories and Mills," *Transactions of the American Institute of Electrical Engineers*, 12 (June 1895), 413–14.

[10] Ibid.

power within factories. Replacing a steam engine with one or more electric motors, leaving the power distribution system unchanged, appears to have been the usual juxtaposition of a new technology upon the framework of an old one. But it was not viewed in this way in the 1880s and 1890s. Shaft and belt power distribution systems were in place, and manufacturers were familiar with their problems. Turning line shafts with motors was an improvement that required modifying only the front end of the system. By the mid- to late 1890s, however, manufacturers were beginning to take a broader view of electricity and building plants with somewhat different power distribution systems. By the end of World War I, electric line shaft drive was not commonly used.[11] A number of older plants, however, continued to use this method of driving machinery until the 1960s.[12]

ELECTRIC GROUP DRIVE

As long as electric motors were simply used in place of steam engines to turn long line shafts, the shortcomings of mechanical power distribution systems remained. According to mechanical engineer H. C. Spaulding, the most serious problems were the large friction losses in the system and the necessity of turning all the shafting in the plant regardless of the number of machines in operation.[13] Spaulding realized that these problems continued to exist because manufacturers had not yet come to view electricity as a means of power distribution within their plants. Production machinery ought to be arranged in groups, he said, with each group of machines driven from a relatively short line shaft turned by its own electric motor. Such a group could be operated most efficiently if the machines ran at similar speeds and if the group exhibited little variation in load.

The first large scale application of such a "group" approach to driving machinery was probably in the General Electric Company plant in Schenectady, New York. Forty-three d.c. motors totaling 1,775 h.p. turned a total of 5,260 feet of shafting. These motors were located in perhaps 40 different shops or departments. Thus the line shafts must have been relatively short, perhaps an average of 100 to 150 feet of shaft per motor; these shafts turned countershafts that drove machinery in the usual manner. The management stated that this system enabled it "to obtain the full measure of economy from absence of friction and the freedom from running any section not in actual use" and that "with

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[11] William B. Cornell, *Industrial Organization and Management* (New York, 1928), pp. 382–84.

[12] Richard S. Mack, personal communication (Central Washington University, Ellensburg, Washington, 1981). Mack is a former employee of a Maine shoe factory that used electric line shaft drive until 1962.

[13] H. C. Spaulding, "Electric Power Distribution," *Power*, 11 (Dec. 1891), 12.

shops covering as these do in floor space close upon twelve acres, it would be simply impossible to concentrate and distribute power in any other economical manner.[14]

General Electric salesmen undoubtedly made good use of their company's experience with electric group drive. Early customers of the company were industries near water power, such as the Columbia, South Carolina, textile mill noted previously. The 1893 proposal of salesman S. B. Paine for powering the mill differed from those of his competitors in two important respects. Polyphase alternating current would be used rather than the much more common direct current, and seventeen 65-h.p. alternating current (a.c.) motors would drive groups of machines. The use of electric group drive rather than electric line shaft drive would reduce airborne dirt and grime; this was particularly important in textile mills. The use of a.c. induction motors rather than d.c. motors would eliminate commutator sparking—a fire hazard in the lint-filled atmosphere of the mill. Finally, the motors were to be mounted on the ceiling so as to occupy no floor space.[15] Paine's proposal was important because it implied electricity was more than a substitute for direct transmission of mechanical power to the plant and more than a means of power distribution within the plant: properly applied, it could improve the overall efficiency of production. The General Electric bid was accepted by the mill owners, even though it was the most costly of those submitted.

Other early adopters of group drive were industries that located near Niagara Falls to take advantage of the low-cost hydroelectric power that became available there in 1895. One of these industries was the nation's largest nut and bolt factory, that of Plumb, Burdict, and Bernard, in North Tonawanda, New York.[16] Their facilities were typical of those designed around electric group drive instead of around line shaft drive: machines were grouped together and belted to countershafts turned by a motor-driven line shaft that served only that particular group of machines (Figure 2C). Group drive offered more flexibility in locating machinery than line shaft drive, often increasing production efficiency. For example, machines that performed related operations—but that might have been located some distance apart with line shaft drive—could now be consolidated in an individual shop or department. The specialized shops of the North Tonawanda plant evidently represented a considerable advance over older plants.

Organizing manufacturing operations into specialized shops or departments was facilitated by group drive because the motor-driven line

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[14] "Electrical Transmission of Power at the Edison Works in Schenectady," *Power*, 12 (Feb. 1892), 2.

[15] Passer, *Electrical Manufacturers*, pp. 303–05; "Electric Power Transmission at Columbia, S.C.," *Electrical World*, 23 (May 12, 1894), 656–57.

[16] "Two Motor Driven Factories," *Power*, 17 (Mar. 1897), 12–13.

shafts and production machinery could be oriented in virtually any direction. In 1897, for example, the Keating Wheel Company built a new factory in Middletown, Connecticut, with shops in six wings perpendicular to the plant's main building.[17] This plant would probably not have been built this way without electric power distribution, as it would have been quite troublesome to turn line shafts in the wings from the shaft in the main building by means of belts. Furthermore, motors turning line shafts in individual shops took up no more floor space than overhead mechanical power distribution. Motors were often mounted on platforms suspended from the ceiling or were attached to the wall; in one machine shop the motor platforms were above the tracks of an overhead traveling crane![18] Obviously, the structural design and internal organization of these and other plants were intimately associated with electric group drive.

As manufacturers gained experience with group drive, countershafts were eliminated and production machinery was belted directly to line shafts, reducing power losses between the motor and the machines and leading to greater consolidation and specialization. Line shafts became shorter; shafts 30 to 50 feet long were typical in many machine shops.[19] Some engineers even held "the extreme view . . . that a motor should be applied to every tool."[20]

From 1899 to 1909, electric drive increased from less than 5 percent of total capacity for driving machinery to 25 percent. During this decade 60 to 70 percent of the electric motor capacity in manufacturing plants consisted of motors powered with electricity generated by the manufacturing establishments themselves. In 1899, 85 percent of manufacturers' generating capacity was in hydroelectric stations, while steam engines represented less than 10 percent of capacity. Over the next ten years, hydro capacity increased only about two-and-one-half times, while steam capacity increased by nearly two orders of magnitude to represent 71 percent of total capacity in manufacturing plants. Thus, the increasing use of electric drive in the late 1890s and first decade of the twentieth century was concurrent with the rise of on-site electricity generation via steam.

Many of the earliest adopters of electric group drive, however, were firms that located near sources of water power. For these plants, power loss between the water turbines and motor shafts was typically 15 to 20 percent.[21] With direct drive, loss between the steam engine and

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[17] Ibid., p. 13.

[18] "Electric Motors at the Ansonia Shops of the Farrel Foundry and Machine Co.," *Power*, 17 (Aug. 1897), 13.

[19] Crocker, "Factories and Mills," pp. 420–21.

[20] Ibid., p. 417.

[21] Passer, *Electrical Manufacturers*, pp. 303–05; C. S. Hussey, "Electricity in Mill Work," *Electrical World*, 17 (May 9, 1891), 343.

machines was at least 30 percent, and this only at optimum, full-load operation. On an efficiency basis alone, electric drive based on hydro power was clearly preferable to direct drive. But for plants employing steam engines, use of electric drive involved two transformations of energy instead of one. Even so, energy consumption was often less with electric group drive.

The greatest reduction in energy consumption upon adoption of group drive came because any department, shop, or group of machines could be operated independently; the motor driving a group of machines could be stopped when the machines were not being used.[22] Conversely, a particular group of machines could be operated without rotating the shafting throughout the entire plant; energy savings could be significant if only part of a plant was working overtime or at night. The ability to shut down or start up selected equipment is taken for granted today, but such ability represented technical and organizational innovation in the 1890s.

Reductions in energy consumption also came with electric group drive because these systems contained less shafting and fewer belts and pulleys than line shaft drive systems; thus, less power was lost to friction in turning shafts. Indeed, estimates of the power required to rotate the shafting in factories using direct drive range between about one-third and three-quarters of the power made available at the plant's steam engine.[23]

But, other factors being equal, energy use with electric group drive was not dramatically lower than with direct drive based on steam. A saving of 20 to 25 percent in the amount of coal used was typical.[24] Nevertheless, even large energy savings would have had a rather minor direct impact on total production costs. This is so because the cost of fuel for electricity generation was relatively small, usually between about one-half and three percent of the total cost of producing a unit of output.[25]

We have already seen that during the late 1890s and early 1900s electric group drive was used in a number of new factories that had been specifically designed around electric power distribution. For these and other firms, electrification of mechanical drive and factory reorganiza-

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[22] Crocker, "Factories and Mills," p. 415.

[23] Hussey, "Mill Work," p. 343; "Electric Power for Isolated Factories," *Electrical World*, 25 (Feb. 16, 1895), 207; "Electricity for Machine Driving," Westinghouse Electric and Manufacturing Company (1898); A. D. DuBois, "Will It Pay to Electrify the Shops?", *Industrial Engineering and the Engineering Digest*, 11 (Jan. 1912), 6–7.

[24] Crocker, "Factories and Mills," pp. 420–21.

[25] G. Richmond, "Electric Power in Factories," *Engineering Magazine* (Jan. 1895); F. B. Crocker, "The Electric Distribution of Power in Workshops," *Journal of the Franklin Institute*, 151 (Jan. 1901), 2, 9; G. M. Campbell, "Machine Shop Practice," *American Machinist* (Jan. 25, 1906), 114; F. H. Penney, "Group Drive and Individually Motorized Drive," *Mechanical Engineering*, 48 (Sept. 1926), 890.

tion went hand in hand. This reorganization often entailed consolidating operations and increasing specialization in individual shops or departments, leading to increased throughput and improved product quality.

Reorganization also frequently involved relocating the steam plant in the basement or in a separate building, thus freeing space in the main building for production and isolating power generation from power use. But regardless of where the steam plant was located, opportunity for spread of fire was dramatically reduced with electric power distribution. This was so because shaft and belt holes in floors and walls were no longer needed; if necessary, production could be contained in individual, fire-proof rooms. Thus, after installing group drive, many manufacturers obtained reduction in fire insurance premiums.[26] Use of electric motors to drive machinery in groups also meant that no single line shaft breakdown could affect the entire plant. Only machines in that shop or portion of the room in which the mishap occurred would be stopped, with the rest of the plant running as before.

Finally, as mentioned earlier, direct drive imposed certain constraints on the size and configuration of individual buildings. It is possible, though conjectural, that expected financial loss in the event of fire or mechanical power outage also acted to limit the physical size of buildings. We do know that with the rise of electric drive, detailed descriptions of very large factory buildings began to appear in the technical literature, and some of these accounts imply that such large installations were uncommon at the time. (See, for example, the descriptions of General Electric's Schenectady plant, of the Westinghouse plant in East Pittsburgh, and of the seven-story building of the Kent and Stanley Company in Providence, Rhode Island.[27]) Thus the indirect benefits of electric group drive appear to have been at least as important as energy efficiency in fostering self-generated electricity in manufacturing around the turn of the century. Electricity was now generally seen as a preferred method of power distribution within manufacturing plants. Group drive was a major form of electric drive through World War I and was vigorously defended as late as 1926.[28] Yet even before the turn of the century, a few innovative manufacturers found it was best to eliminate shafting altogether and run each machine with its own electric motor.

ELECTRIC UNIT DRIVE

During the 1890s most engineers advised against running any but the largest machines with individual electric motors. This was primarily because the power capacity required to drive a group of machines was

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[26] "Electricity for Machine Driving."

[27] "Electrical Transmission of Power," p. 2; "Electricity in Industrial Plants," *Manufacturers' Record*, 27 (July 19, 1895), 392–93; Crocker, "Factories and Mills," pp. 421–22.

[28] Penney, "Group Drive," p. 890.

much less than the sum of the capacities required to drive each machine separately. By 1904, however, most observers believed that individual (or "unit") drive would eventually replace other techniques for driving nearly all large tools. But some enthusiasts, such as engineer G. S. Dunn, had a broader outlook:

> Not very long ago many hesitated to assert definitely that the motor drive had come to stay, while today it is only a question of what kind of motor drive. I feel perfectly confident that the individual drive will soon be adopted for even very small machines.[29]

The next two sections review the reasons for the promise of electric unit drive.

Energy and Direct Cost Savings

With unit drive, a motor was usually mounted right on the machine being driven (Figure 2D). Motor and machine drive shaft were often connected by a belt and pulleys or by gears. Sometimes motor armature and drive shaft were directly linked via a key-and-slot coupling.

Unit drive used less energy than group drive for the same reasons that group drive used less energy than line shaft drive. Unit drive entirely eliminated power losses due to friction in rotating line shafts and countershafts, sometimes almost doubling overall, full-load efficiency of power production, transmission, and distribution.[30] More important, no energy was wasted turning shafts with some machines out of service.

A manufacturer's total cost of driving machinery—consisting not only of energy costs, but also of capital, labor, and materials costs—was often somewhat lower with unit drive than with group drive. For this to occur, savings in energy, labor, and materials had to offset any increases in capital costs.

Capital costs could be high with unit drive because the total capacity of motors for unit driving was often five to seven times the capacity of a single motor for group driving of the same machines.[31] With unit drive, each motor had to be of sufficient capacity to handle the maximum demand of its machine; with group drive, the motor could be sized to take advantage of load diversity. That is, only the average load of a group (plus a safety margin) needed to be met because each machine in the group operated only part of the time; rarely did all the machines in a group demand maximum power simultaneously.

With adoption of unit drive the total capacity of electric motors in a plant increased dramatically, but the actual peak power need of the plant did not necessarily increase. In fact, peak demand often decreased somewhat due to absence of friction loss in shafts and belts. In

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[29] Day, "Machine Tools," p. 337.

[30] Even so, until the 1920s the overall efficiency of providing mechanical power to machinery seldom exceeded about 12 percent—even with electric utility generation.

[31] Penney, "Group Drive," p. 890.

principle, this permitted installing a proportionally smaller power plant, with capital cost savings. Furthermore, factory buildings could be of lighter and cheaper construction since their roofs no longer had to support heavy line shafts, countershafts, and pulleys. The elimination of this mechanical power distribution system effected the greatest saving, sometimes offsetting the first cost of additional motors and wiring.[32] Nevertheless, the cost of equipping a plant with electric unit drive was usually somewhat higher than installing electric group drive.[33]

Labor and materials costs, however, were generally lower with unit drive. There were no belts to tighten and adjust, and no drip oilers to fill. Thus, lower costs of energy, labor, and materials were probably often sufficient to offset the capital cost penalty of electric unit drive, giving this technique a slight cost advantage over group drive or line shaft drive.

But savings in the cost of mechanical drive were not terribly important. As noted previously, the cost of fuel for electric power generation or the cost of purchased electricity was a minor item, usually between about one-half and three percent of the total cost of producing a unit of output. Since the cost of energy was a major fraction of the total cost of mechanical drive, it follows that the cost of driving machinery was a small component of total production cost—certainly less than one-tenth and probably closer to one-twentieth of total cost per unit of output.[34] Thus, even a large reduction in the cost of mechanical drive would have had a minor direct impact on production costs.

Electricity: A Lever in Production

Early in the twentieth century, manufacturers began to recognize that direct cost savings with electric unit drive were almost insignificant compared to other benefits of using this technique. According to AIEE member Oberlin Smith,

> The problem talked much about until quite recently has been whether we should put in motors at all, because we did not know whether they were going to take more power or not . . . that is a point of very little importance, compared with the total expenses of the shop. It doesn't matter if it is 5 or 10 or 20 percent, considering the great advantages we are going to get in all these other ways.[35]

S. M. Vauclain, superintendent of the Baldwin Locomotive Works, reports his company's favorable experience:

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[32] DuBois, "Will It Pay," p. 9.

[33] Crocker, "Factories and Mills," p. 414; DuBois, "Will It Pay," p. 8; Crocker, "Electric Distribution of Power," p. 2; Penney, "Group Drive," p. 892.

[34] In recent times energy has represented approximately three-quarters of the total cost of driving production machinery. See David B. Reister and Warren D. Devine, Jr., "Total Costs of Energy Services," *Energy*, 6 (1981), 305–15.

[35] Crocker, "Factories and Mills," p. 427.

> In conclusion, while the question of the saving in power which the adoption of electric motors permitted was of importance, it was by no means the deciding factor; I would have put in electric driving systems not only if they saved no power, but even if they required several times the power of a shaft and belting system to operate them.[36]

Electric equipment sales engineers began to shift their emphasis from energy and direct cost savings to "indirect savings." According to an engineer with the Crocker-Wheeler Electric Company,

> There were many factories which introduced electric power because we engaged to save from 20 to 60 percent of their coal bills; but such savings as these are not what has caused the tremendous activity in electric power equipment that is today spreading all over this country . . . those who first introduced electric power on this basis found that they were making other savings than those that had been promised, which might be called indirect savings.[37]

Thus, with the advent of unit drive, electricity was beginning to be seen as more than an economical means of power distribution within factories; to many, it was a "lever" to increase production.

Manufacturers often estimated the additional production they could ascribe to electric unit drive and reported their experiences at technical society meetings. At a meeting in 1901 Professor F. B. Crocker summarized a number of these reports:

> It is found that the output of manufacturing establishments is materially increased in most cases by the use of electric driving. It is often found that this gain actually amounts to 20 or 30 percent or even more, with the same floor space, machinery, and number of workmen. This is the most important advantage of all, because it secures an increase in income without any increase in investment, labor, or expense, except perhaps for material. In many cases the output is raised and at the same time the labor item is reduced.[38]

How did electric unit drive facilitate these increases in output and productive efficiency?

Increased Flow of Production. Unit drive gave manufacturers flexibility in the design of buildings and in the arrangement of machinery to maximize throughput. No longer were machines grouped and placed relative to shafts. Machinery could now be arranged on the factory floor according to the natural sequence of manufacturing operations, minimizing handling of material. The ability to arrange machinery irrespective of shafting made all space in the factory equally useful and not only as storage, as heretofore. Such flexibility, for example, allowed the U.S. Government Printing Office to add forty printing presses: "Although it did not increase the actual floor area, it did materially increase our working floor space."[39] Furthermore, a machine's position could be

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[36] Crocker, "Electric Distribution of Power," p. 8.

[37] Ibid., p. 9.

[38] Ibid., pp. 6–7.

[39] Ibid., p. 19.

changed readily, without interfering with the operation of other machines.

Large, engine-driven overhead cranes were used on erecting floors before 1900, but overhead mechanical power transmission precluded cranes almost everywhere else. By eliminating shafting, electric unit drive left clear and unobstructed passages and headroom, and allowed use of overhead traveling cranes in any part of a plant. One speaker at the 1895 AIEE meeting expected small electric cranes to revolutionize material handling:

> I do not think any of us rightly conceive of the great convenience and rapidity of work that is coming from the handling of our small loads by this means . . . Now, for anything but very light work which the men can pick up and put right in the machine, there is a considerable waste of time putting work in and out of machines—more than any one would realize, and often amounting to more than that required for the actual cutting. All this is going to be one of the direct results of the clear headroom brought about by the use of motors.[40]

Nine years later electric cranes were being called an "inestimable boon" to production;[41] by 1912, the importance of clear headroom for cranes was "so generally recognized as to require no comment.[42]

But unit drive did more than permit easier moving of work to machines; it also made it possible to move machines to the work. Portable power tools could now be readily applied to any part of a large workpiece. According to a 1912 account, such tools "played an active and extensive part in increasing the output in structural iron works, locomotive works, and modern shops of almost every description.[43]

Finally, as group drive had reduced the effect of a motor malfunction or breakdown in the mechanical power distribution system to the affected group of machines, so unit drive further limited the disruption of production to the single malfunctioning machine.

Improved Working Environment. Absence of overhead mechanical power transmission led to improvements in illumination, ventilation, and cleanliness. Formerly, mazes of belts practically precluded shadowless lighting. With unit drive, lights could be provided in places formerly occupied by belts, pulleys, and shafts. Some new buildings incorporated skylights, thus improving ventilation as well as illumination. With line shaft or group drive, continuous lubrication of shafting added oil and grease to the working area and moving shafts and belts kept grease-laden dust circulating. Walls and ceilings became dirty rapidly and were rarely cleaned or painted because of the difficulty of getting around the shafting. Factories were vastly cleaner and brighter after adoption of

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[40] Crocker, "Factories and Mills," p. 427.
[41] Day, "Machine Tools," p. 337.
[42] DuBois, "Will It Pay," p. 4.
[43] Ibid.

unit drive, and many observers felt this had a very positive impact upon the quantity and quality of work.[44]

Improved Machine Control. Belt slippage, common with group drive, caused the speed of some machines to vary with load, reducing the quantity and quality of output.[45] Furthermore, the two or three pulleys used on most drive shafts and countershafts limited the number of operating speeds. Often work was turned out at a slower than maximum rate.[46] In addition, valuable time could be lost during speed changes if the operator had to leave his work to shift the belt between pulleys. Unit drive practically eliminated these problems. Individual motors—with a minimum of transmission apparatus—maintained relatively steady machine speed. Where necessary, electrical techniques allowed the operator conveniently to vary the speed of his machine.

Until after the turn of the century direct current motors provided almost all industrial electric drive. The prevailing type of d.c. motor was the shuntwound machine, which was easily varied in speed over a range of 3 or 4 to 1 by changing a rheostat. With a gear box, a wider range of speeds cound be obtained. In some cases, speed was changed by varying the voltage applied to a constant-speed motor via switching between multiple-voltage circuits installed in the factory or via the "Leonard system." The latter was a motor-generator-working motor combination in which changing the field excitation of the generator changed the speed of the working motor.

The alternating current polyphase induction motor was invented by Nikola Tesla in 1888 and marketed four years later by Westinghouse. For the same output, a.c. motors were superior to d.c. motors in a number of respects: they were smaller, lighter, and simpler, did not spark, required very little attention, and were quite a bit cheaper. But a.c. motors had one principal drawback: their speed could not be varied without seriously impairing performance. Frequency, not voltage, governs the speed of an induction motor, and it was not practical to provide variable-frequency current. For a time, whether a.c. or d.c. motors were employed depended on which current was available and whether it was necessary or desirable to vary the speed of machines. But after the completion of the initial phase of the a.c. generating system at Niagara Falls in 1895, utilities increasingly supplied a.c. power. Now compatibility with the rapidly growing utility system was another of the a.c. motor's advantages. By 1901, many engineers felt that if efficient speed variation could be devised, the induction motor would be an important

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[44] Crocker, "Factories and Mills," pp. 429–30; "Electricity for Machine Driving;" DuBois, "Will It Pay," p. 8; Crocker, "Electric Distribution of Power," p. 4.

[45] Gordon Fox, *Electric Drive Practice* (New York, 1928), pp. 2, 8, 10; Wilhelm Stiel, *Textile Electrification: A Treatise on the Application of Electricity in Textile Factories* (London, 1933), pp. 111–16.

[46] DuBois, "Will It Pay," p. 5.

step toward the "ideal workshop"—a shop with a motor driving each tool or machine.[47]

But during the first decade of the twentieth century, manufacturing methods began to call for more special-purpose machine tools, and these operated over comparatively narrow speed ranges. At a technical meeting in 1904, engineer H. B. Emerson observed

> The amount of speed variation required, of course, varies with the installation; but it seems as though the trend of industry is toward specialization, and where this specialization increases, the need of a large range of speed control decreases as one machine does its specific work, and this same class of work comes to it day after day and week after week. In such installations standard, or nearly standard, apparatus can be used.[48]

Of course, the availability of relatively cheap induction motors and the alternating current to run them were associated with this trend toward specialization. It is not clear whether increasing use of a.c. motors was an important cause of the specialization or a result of it. In either case, manufacturing's need for speed variation that initially held back the spread of a.c. motors diminished. Increasing use of a.c. motors and the rise of unit drive went hand in hand, enhancing quantity and quality of output via steady speed and convenience of control.

Ease of Plant Expansion. The first quarter of this century was a time of rapid growth in manufacturing. Transportation equipment, electrical equipment and supplies, and petroleum refining experienced the fastest growth rates, production gains averaging around 10 percent per year over the entire period, while some firms occasionally saw much higher year-to-year increases in demand for their products.[49] A number of these rapidly growing firms felt that mechanical power distribution systems imposed constraints on expansion of their plants.[50] With line shaft drive, the original power distribution system had to be designed with provision for expansion, or it had to be replaced entirely; ad hoc additions to the system reduced efficiency and increased fluctuations in speed of driven machinery in the new parts of the plant.[51] Even with electric group drive, plant expansion often required undue rearrangement of machinery. Once a plant converted to electric unit drive, however, the power distribution system no longer hampered expansion of production facilities. Departments could be enlarged and buildings could be added readily. Costly hanging or rehanging of shafts was unnecessary, and production could continue even during construction

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[47] Crocker, "Electric Distribution of Power," pp. 24–28.

[48] Day, "Machine Tools," p. 431.

[49] U.S. Bureau of the Census, *Historical Statistics of the United States, Colonial Times to 1970, Bicentennial Edition, Part 2*, Series P 40–67 (Washington, D.C., 1975).

[50] Crocker, "Factories and Mills," p. 428.

[51] Stiel, *Textile Electrification*, pp. 111–16.

of the new works. In a case study of the Scovill Manufacturing Company of Waterbury, Connecticut, historian E. B. Kapstein argues that the removal of constraints on expansion of production was the primary reason for the company's switch to electric unit drive.[52]

In summary, although unit drive used less energy and sometimes cost less than other methods of driving machinery, manufacturers came to find these savings to be far less important than their gains from increased production. In essence, electric unit drive offered opportunity—through innovation in processes and procedures—to obtain greater output of goods per unit of capital, labor, energy, and materials employed. Electricity had come to be viewed as a factor in improving overall productive efficiency.

MARKET PENETRATION

Figure 3A outlines the trend toward freeing industrial production from constraints imposed by power transmission and distribution—a trend that culminated during the 1920s with the widespread use of unit drive. Since no comprehensive data were ever collected on power distribution systems in use, the time lines of the figure are based on three bodies of evidence that indicate that unit drive did not become the predominant form of electric drive until after World War I.

First, the merits of driving machines in groups or driving them individually were discussed in the technical literature throughout the first quarter of the twentieth century. Between 1895 and 1904, this subject was vigorously debated in meetings of technical societies; neither technique could be said to be best in all cases.[53] Since such meetings have always been forums for discussion of new concepts and developments, those who advocated unit drive were probably well ahead of established practice. And, over 20 years later, group drive was still being strongly recommended for many applications. In 1926, F. H. Penney of the General Electric Company's Industrial Engineering Department reviewed the place of unit drive vis-a-vis group drive at the New Haven, Connecticut, Machine Tool Exhibition. He concluded.

> The experience of the author in the motor-application field inclines him to the belief that, unless all of the operating conditions are known, it is difficult to decide which would be the better of the two methods. . . . Generally, the author thinks that at the present time individual drives seem to predominate—i.e., as far as newly installed equipment is concerned.[54]

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[52] Ethan B. Kapstein, "Industrial Power at Scovill Manufacturing Company: A Research Note" (Unpublished manuscript, Harvard University, 1981).

[53] Day, "Machine Tools," p. 348; Crocker, "Factories and Mills," p. 411; Crocker, "Electric Distribution of Power," p. 23.

[54] Penney, "Group Drive," pp. 889, 969.

Two textbooks printed in 1928 also make it clear that there were many situations in which group drive was justified, but that the tendency during the 1920s was toward exclusive use of unit drive.[55]

Second, machines had to be made compatible with motors. Production machinery had traditionally been built with drive shafts and pulleys for use with direct drive systems. Even in 1901, machine tools were not generally built to be directly connected to an electric motor, and the control and performance of some machines were only marginally better with unit drive than with line shaft or group drive.[56] The situation improved a few years later as better quality steel became available and brought about changes in the design of machine tools. Often these new machines provided for the mounting and direct connection of electric motors.[57] In 1904 several of the largest manufacturers of lathes adapted 30 percent of their product line for unit drive.[58] But according to engineer F. B. Duncan, more significant changes were needed:

> No permanent advance in electrical operation of machine tools will be made until the motor and the tool are designed for each other as much as the old cone pulley was designed for the machine on which it was used . . . What is needed (and this cannot be emphasized too strongly) is a complete re-design of present machine tools with motor operation alone in view.[59]

Through 1904 the means of providing power to production machinery had changed significantly while the machines themselves had changed very little. Now, however, the spread of the culminant form of mechanical drive and the development of new machines were closely related. Yet, progress toward the "complete re-design" of tools advocated by Duncan was not as rapid as he might have hoped. A 1928 textbook indicates only a "trend toward incorporating the motor as an integral part of the machine tool."[60] Thus, machines designed specifically for unit drive were probably not in wide use until after World War I.

The third reason for believing that unit drive was not widespread until the 1920s is that electricity did not become widely available until the rise of the electric utilities. In 1909, electric drive accounted for slightly less than 25 percent of total capacity for driving machinery; by 1919, electric motors represented over 53 percent of the total horsepower used for this purpose. This major transition was concurrent with changes in the supply of electricity. In 1909, 64 percent of the motor capacity in manufacturing establishments was powered by electricity generated on

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[55] Cornell, *Industrial Organization*, pp. 382–84; Fox, *Electric Drive Practice*, pp. 8, 355.

[56] Crocker, "Electric Distribution of Power," p. 8.

[57] Day, "Machine Tools," pp. 333, 338.

[58] Ibid., p. 323.

[59] Ibid., pp. 338–39.

[60] Fox, *Electric Drive Practice*, p. 82.

site; ten years later 57 percent of the capacity was driven by electricity purchased from electric utilities. Although electric generating capacity in manufacturing continued to increase over this period, electric utilities were expanding so fast that after about 1914 their generating capacity exceeded that in all other industrial establishments combined.

Technical and entrepreneurial innovation promoted the rapid growth of electric utilities. Increasing use of alternating current after 1895 facilitated economical long-distance transmission of power. Central stations could be fewer and larger, and a greater market could be served. But economies of scale were not significant until after introduction of the steam turbine. The unit cost of turbines was lower and decreased more rapidly with size than that of steam engines, and the turbine's much higher speed permitted cheaper electric generators to be used.[61] The use of turbines grew rapidly, achieving predominance around 1917, largely at the expense of steam engines.

The steam turbine led to lower costs for utility electricity, but this technology was not the only innovation that enabled utilities to compete successfully with on-site generation. In order to take advantage of the scale economies offered by turbines, the demand for electricity and generating capacity had to increase concomitantly. One way of ensuring this was to consolidate small utilities and their markets into a single large system, as was done, for example, by Samuel Insull, president of the Commonwealth Edison Company.[62] Another way was to market a complete "energy service." Because productivity gains upon conversion to unit drive were not automatic, there was need for intelligent application and direction.[63] Thus, for example, the Detroit Edison Company announced in 1905 that they would lend motors to manufacturers and provide—at no charge—the engineering and installation work needed for their proper application.[64] Miss Sarah Sheridan, head of the company's sales department, used engineers to help sell a complete system of mechanical drive service, and greater productivity was an integral part of this service.

Of course, utilities were less successful in selling mechanical drive services to firms that already generated their own electricity than to those that were building new facilities. Few manufacturers were willing to write off installed equipment prematurely; a new plant, on the other hand, could be designed around utility power and unit drive. Many small firms building new facilities could not afford their own electric power plants; often they had rented shaft power along with floor space

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[61] Passer, *Electrical Manufacturers*, pp. 310–13.

[62] Thomas P. Hughes, "The Electrification of America: The System Builders," *Technology and Culture*, 20 (Jan. 1979), 139–53.

[63] Day, "Machine Tools," pp. 323–26, 340–41.

[64] Raymond C. Miller, *Kilowatts at Work: A History of the Detroit Edison Company* (Detroit, Michigan, 1957), pp. 159–60.

in large buildings. Utilities made electricity available to these small manufacturers for the first time; in some cases this class of customer was the major source of growth in demand.[65] Thus, the utilities played an important role in increasing the penetration of electric unit drive, and their influence was particularly strong during the second decade of this century.

SUMMARY AND CONCLUSIONS

The shift from steam power to electric power was fundamentally different from the pre-1870 transition from water power to steam. That shift in the way mechanical power was produced was not accompanied by new methods of power transmission and distribution. Adoption of steam did not involve anything like the major changes in factory design and machine organization that went hand in hand with electrification; rather, manufacturers adopted steam power primarily for reasons of locational and seasonal availability and of direct cost.[66]

The cost of driving machinery, however, was not the most important factor in the adoption of electric unit drive. This transition was primarily motivated by manufacturers' expectations of significant indirect cost savings. Electricity had a value in production by virtue of its form (a "form value") that exceeded savings in direct costs.

The form value of electricity was due to the precision in space, in time, and in scale with which energy in this particular form could be transferred. Motors could convert electrical energy to mechanical energy precisely where the conversion was needed—the drive shaft of a machine. This conversion and transfer of energy could be exactly controlled with respect to time—that is, it could be started, stopped, or varied in rate as needed. And finally, electric motors could be accurately matched to the power requirements of machines. Thus, electric unit drive was an extremely flexible technique for driving machinery; and, because of this flexibility, manufacturers could turn their attention away from problems of power production and distribution and toward improving the overall efficiency of their operations.

Moreover, a fundamental change in viewpoint preceded and accompanied exploitation of the unique flexibility of electricity in production. Until the 1890s, most manufacturers viewed electricity in a limited sense: it was simply a good way to transmit mechanical power to factories. In 1891, engineer H. C. Spaulding pointed out that electricity was more than this—it was the best way to distribute power within

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[65] Ibid.

[66] Kapstein, "Industrial Power"; Jeremy Atack, "Fact in Fiction? The Relative Costs of Steam and Water Power: A Simulation Approach," *Explorations in Economic History*, 16 (1979), 409–37; Jeremy Atack, F. Bateman, and T. Weiss, "The Regional Diffusion and Adoption of the Steam Engine in American Manufacturing," this JOURNAL, 40 (June 1980), 281–308.

factories. Two years later, General Electric salesman S. B. Paine demonstrated that electricity could be used to benefit produciton in more indirect ways as well. And beginning in 1895, a series of discussions led by Professor F. B. Crocker all but confirmed the innovation view that electricity could serve as a lever in production. The ensuing 30 years saw increasing penetration of electric drive accompanied by numerous innovations in factory design and methods of production—many of which were possible only because of the precision in space, in time, and in scale with which energy as electricity could be transferred.

The period immediately following World War I was one of particularly rapid change. During the late 1910s and the 1920s, electric unit drive became the most common method of driving machinery and electric utilities became the principal providers of power for manufacturing. Efficiencies in production made possible by unit drive are manifested by significant increases in indexes of productivity in manufacturing beginning just after the war. The shift to the utility sector of resources used in electricity generation contributed to the rise of these indexes and also to the sharp increase in power capacity per unit of capital input in manufacturing. A more important reason for this latter upswing, however, is that unit drive required several times as much motor capacity as other forms of electric drive. Finally, unit drive clearly used less energy per unit of output than other methods of driving machinery. Thus, both energy savings and increased productivity in manufacturing contributed to the dramatic change in trend of the energy-GNP ratio around 1920.