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Research Memorandum

AN HISTORICAL PERSPECTIVE ON THE VALUE OF ELECTRICITY IN AMERICAN MANUFACTURING

Warren D. Devine, Jr.

Institute for Energy Analysis
Oak Ridge Associated Universities

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September 1982

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ABSTRACT

Use of electricity in manufacturing is increasing faster than use of fuels. This paper draws upon primary sources to recount the history of the first major shift to electricity in industry and provides a perspective on changes that accompanied electrification. 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 electrification of mechanical drive proceeded in three stages: at first, large electric motors simply replaced prime movers in turning long line shafts; then, machines were divided into groups along shorter shafts, and each group was powered by a separate smaller motor; finally, shafting was eliminated and each machine was run by its own electric motor. The use of electricity reduced slightly the energy required to drive machinery and sometimes the total cost of running machinery. More important, electric drive enabled industry—through innovation in factory organization—to get greater output per unit of capital and labor input. This increase in productivity in manufacturing strongly influenced the relationship between energy consumption and gross national product in the first half of the twentieth century.

ACKNOWLEDGMENTS

The author acknowledges the valuable contributions of several individuals to this research. Sam Schurr of the Electric Power Research Institute, who initially explored this subject in the late 1950s, provided support and overall direction; Ethan Kapstein of Harvard University made numerous suggestions that helped identify issues, focus effort, and improve presentation; Elliot Sivowitch of the Smithsonian Institution provided access to primary sources in the curator's collection and in the "pit"; and Richard Mack of Central Washington University and Rollin Olson of Johns Hopkins University gave the benefit of their experience and unpublished research during the formative stages of this work.

AN HISTORICAL PERSPECTIVE ON THE VALUE OF ELECTRICITY IN AMERICAN MANUFACTURING

I. INTRODUCTION

During the latter part of the nineteenth century, American manufacturers produced mechanical power from falling water and combustion of coal. Networks of shafts and belts were used to transmit power from centrally located waterwheels, water turbines, and steam engines to production machinery on factory floors. The organization of manufacturing processes within factories was constrained by the power distribution system. The advent of electricity made possible a fundamental change in manufacturing. As electric motors were mounted on individual machines, manufacturing operations could be laid out in any sequence that maximized throughput. Substitution of electric power for steam power reduced the energy needs and the total cost of driving machinery; more important, however, this substitution stimulated innovation in factory organization and management, which increased output of goods per unit of capital, labor, and materials employed. With this recognition, electricity rapidly became the dominant form of energy used to drive machines in American industry. By 1929, just 45 years after their first use in a factory, electric motors accounted for over three-quarters of total power capacity used to drive machinery.

Today, manufacturers use electricity in innumerable ways. Electricity drives pumps, lathes, and conveyors; electric furnaces melt steel scrap and reduce alumina; electronic instruments acquire data for analysis by computers and use in control of processes; and electricity illuminates factories, powers office equipment, and conditions the working environment. The diverse applications of electricity in industry can be divided into three broad categories: mechanical power for driving machines ("mechanical drive"), support services, and electro processes.

Over half the electricity used in manufacturing powers motors that drive machines, and these motors account for over 85 percent of total mechanical drive capacity. Support services--electronic information handling, illumination, space conditioning, and office equipment--now account for 10-20 percent of the electricity used by manufacturers. Except for space heating, support services--like mechanical drive--are largely electrified. About one-third of the electricity used in manufacturing is used in electro processes: the heating of materials in electric furnaces, electrolysis, electroforming, and other operations that are unique to electricity. But most manufacturing processes that require heat now use fuel, not electricity, to attain desired temperatures. Indeed, the heating value of the fuel used for process heat is on the order of 15 times that of the electricity used in electro processes (1). Thus, electricity is clearly the primary energy form used in all manufacturing operations other than heating; the production of process heat, however, is the main use of energy in industry.

This pattern of industrial energy consumption is changing. In major industries, total energy consumption per unit of output has declined over the past several decades. At the same time, electricity consumption per unit of output has increased--an indication of growing electrification. Burwell (2) shows that electricity is increasingly displacing fuels used for process heat, accompanied by reductions in primary energy consumption. He argues that U.S. industry seems poised for another major shift toward use of electricity—this time for process heat, particularly at high temperatures. Such a shift, should it occur, could bring significant changes in overall energy use and productivity in American manufacturing.

We therefore feel it is useful to review the history of the first major shift to electricity in industry--the electrification of mechanical drive. The transition from steam engines and shaft and belt drive to electric motors mounted directly on machinery had significant effects on energy consumption and productive efficiency earlier in this century. We cannot say whether history will be repeated; but a look at history might help us to view present changes in energy use in a broader perspective.

In the next section we discuss important changes in the productive efficiency of American manufacturing and of the economy as a whole around the end of World War I. Reasons for these changes are reviewed, including the increasing use of electricity in production. The following four sections describe ways mechanical power was produced and distributed in manufacturing industries between about 1880 and 1930. Reasons for shifts from one method of driving machinery to another are reported: improvements in overall efficiency of production, energy savings, and reductions in total cost of driving machinery. Contemporary journals provide the basis for this analysis, both because of the lack of secondary sources and because of our desire to view the process of industrial electrification from the standpoint of a witness. Finally, in the concluding section, we identify some intrinsic aspects of electricity that gave it particular value in production, and we offer some perspectives on energy use and productivity in manufacturing today.

II. EVIDENCE OF REVOLUTION

A measure of the overall efficiency with which our society uses energy to produce goods and services is the ratio of total primary energy* consumed in a given year to the real gross national product (GNP) for that year. The energy efficiency of the economy decreased steadily (the ratio increased) from 1890 to 1920. Then a dramatic change in trend occurred, and over the last 60 years the American economy has become more energy efficient (Table 1 and Figure 1). Although the ratio of energy consumption to GNP has increased and decreased a number of times since 1920, these fluctuations are not as significant as the revolution that occurred just after World War I.

In 1960, Schurr and Netschert (6) examined a number of trends that are consistent with the relationship between energy consumption and GNP exhibited in Figure 1. First, the basic structure of the national economy changed between the 1890s and the 1950s. Manufacturing—the sector that has historically used the greatest share of primary energy--became an increasingly important part of the economy over the entire period. However, output in manufacturing grew more slowly relative to GNP after 1920 than before. Such a slowdown in the relative growth of the major energy-using sector could have contributed to the change in trend of energy consumption relative to GNP around 1920.

Second, the overall productive efficiency of the national economy—as measured by real gross product per unit of capital and labor input--increased persistently between the 1890s and the 1950s. But the increase was considerably faster after World War I than before--rising from an average annual rate of improvement of 1.3 percent between 1889 and 1919 to 2.1 percent between 1919 and 1957 (9). An analogous trend occurred in manufacturing (Table 2 and Figure 2). Labor productivity in manufacturing increased at an average annual rate of 1.3 percent before 1919 and 3.1 percent after, while the downward trend in capital productivity reversed. Schurr and Netschert argue that the same influences that increased the efficiency with which capital and labor were employed also increased the efficiency with which energy as employed.

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*Total primary energy is the sum of the coal, oil, and gas actually consumed and of the fossil fuel it would have taken to produce the electricity generated by hydroelectric and nuclear power plants.

TABLE 1. ENERGY CONSUMPTION AND GROSS NATIONAL PRODUCT, 1890-1980

Year	GNP (10^9 1972 Dollars)	Energy Consumption (10^{15} Btu)	Energy ÷ GNP (10^3 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 reference 3, Series F 1-5, converted from 1958 dollars to 1972 dollars using implicit price deflator 0.6604; GNP 1910-1975 is from reference 4, Tables 1.2 and 1.22; GNP 1980 is from reference 5. Energy consumption 1890-1955 is from reference 6, Table 48, mineral fuels and hydropower; energy consumption 1960-1970 is from reference 7, Table 1; energy consumption 1975-1980 is from reference 8.

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. Colume 4 is an index of output per manhour: Column 3 ÷ Column 1. Column 5 is an index of output per unit of capital input: Colume 3 ÷ Column 2.

Source: Reference 9, Table D-1.

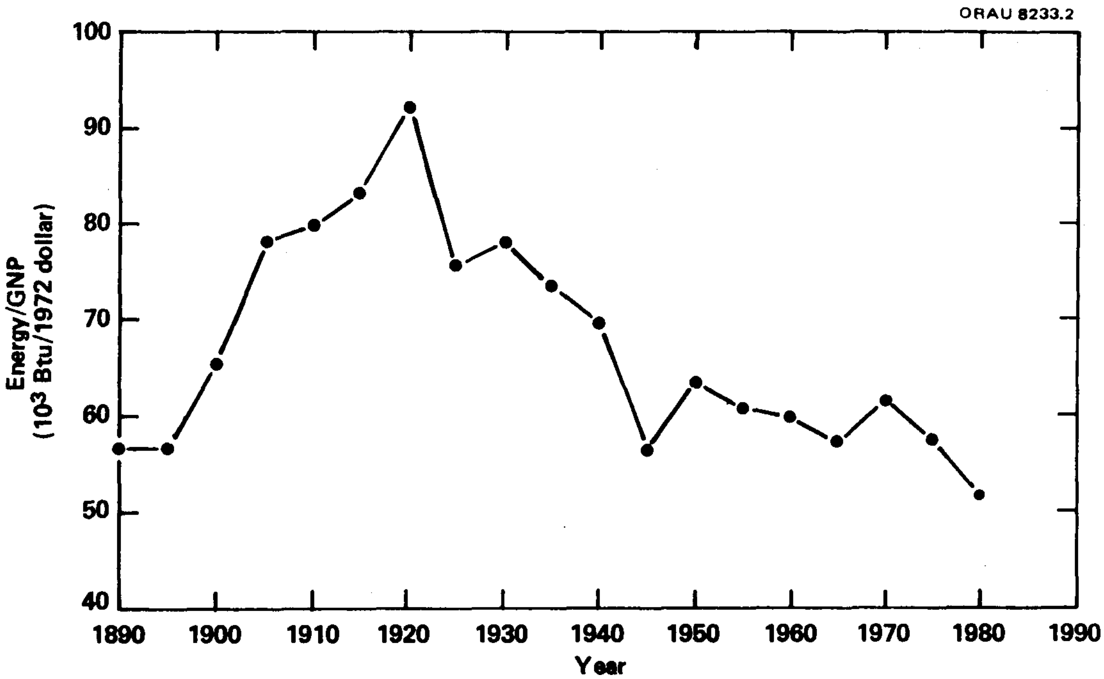

Figure 1. Energy Consumption per Dollar of Real Gross National Product, 1890-1980

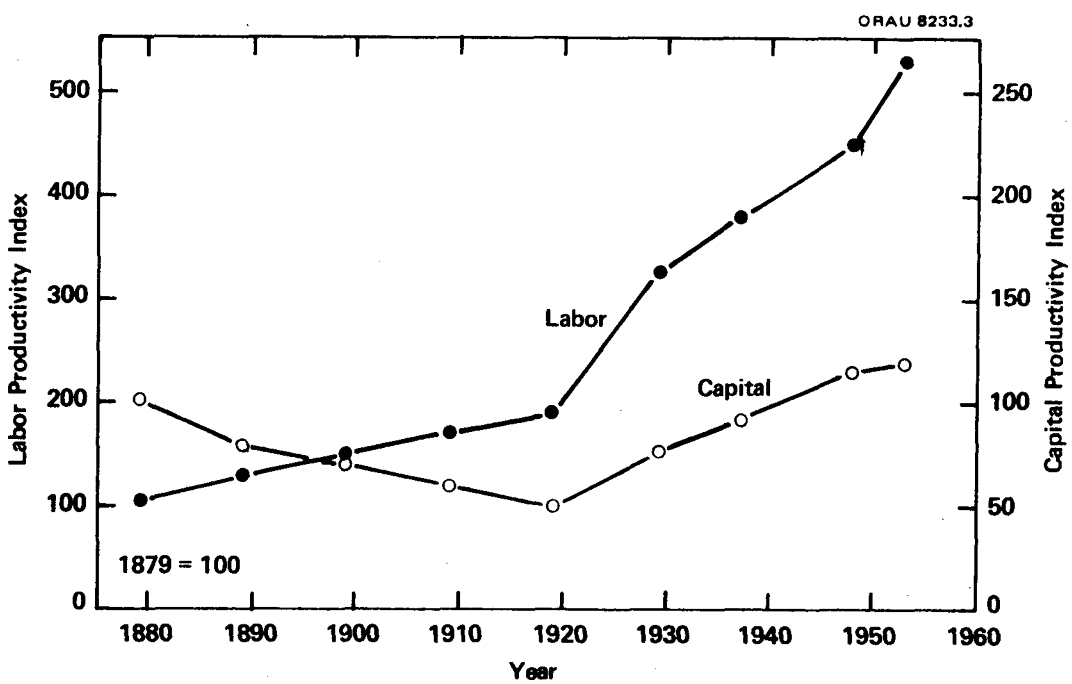

Figure 2. Indexes of Capital and Labor Productivity in Manufacturing, 1879-1953

One of these influences--the "managerial revolution" in American business--is the subject of a recent book by historian A. D. Chandler (10).

According to Chandler, the post-World War I productivity improvement coincided with the maturing of the most powerful institution in the American economy--the multiunit business administered by salaried managers. During the latter part of the nineteenth century, expanding markets and technical progress increased the flow of materials through ever more complex production and distribution processes, rendering market mechanisms less effective in coordinating activities. Multiunit enterprises were established when administrative coordination of the flow of goods from one business unit to another could achieve greater productivity and higher profits than market coordination. Administrative coordination meant lower information and transactions costs; more important, it permitted more intensive use of facilities and personnel, and reduction of inventories.* Between World War I and 1950 a small number of enterprises and their managers came to dominate major sectors of the economy; according to Chandler, rarely has an institution grown to be so important and so pervasive in so short a time.

Thus the rise in importance of manufacturing and improvements in its organization are consistent with trends in the overall energy efficiency of the economy (Figure 1). But probably even more significant changes took place during this period in the forms of energy that were produced and used. 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. Indeed, 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

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*An excellent example is the Ford Motor Company during the early 1920s. Henry Ford expanded his enterprise to include mining, lumber production, glass manufacture, shipping, and rail freight; in so doing he came to control the flow of raw materials and processed goods to and from his factories just as he controlled the flow of fabrication within his factories. In a five year period Ford drastically reduced his stockpiles and warehouses, eliminating over $200 million in inventories and cutting the time from ore at the mine to finished automobile from 14 to 3.4 days (11, 12).

than in the latter part of the nineteenth.* These increases in thermal efficiency are reflected in the decline in energy consumption relative to GNP after World War I.

Another reason 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. The thesis of this paper is that the shift from steam and water power to electricity in manufacturing not only increased the thermal efficiency of energy use but, more important, enhanced overall productive efficiency; thus electrification strongly influenced the relationship between energy and GNP in the first half of the twentieth century.

The extremely rapid penetration of electric motors in manufacturing is central to the development of this thesis. 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 3).

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 a 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 4). 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; however, as we have seen, just the opposite actually occurred.

Thus, to more fully understand the trends exhibited in Figures 1-4 and their relation to one another, it is necessary to look beyond data for the economy as a whole or for the manufacturing sector. Ideally, one would like to be able to view the shift to electricity in production from the standpoint of

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*This was true despite the fact that the generation of electricity--with large thermal losses--grew much more rapidly than total primary energy consumption. Two reasons are (1) electricity as yet represented a small part of total energy and (2) the efficiency of electricity generation increased by more than a factor of four between 1905 and 1955.

TABLE 3. SOURCES OF MECHANICAL DRIVE IN MANUFACTURING ESTABLISHMENTS, 1869-1939

(capacity in 10^3 horsepower)

	Direct Drive (Prime Movers)					Indirect Drive	Total
Year	Steam Engines (1)	Steam Turbines (2)	Internal Combustion Engines (3)	Water Wheels and Turbines (4)	Total Direct Drive (5)	(Primary and Secondary Electric Motors) (6)	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 reference 13, pp. 66-69 and Tables 14 and E-6. Columns 5 and 6 are from reference 13, 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
	10^3 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.

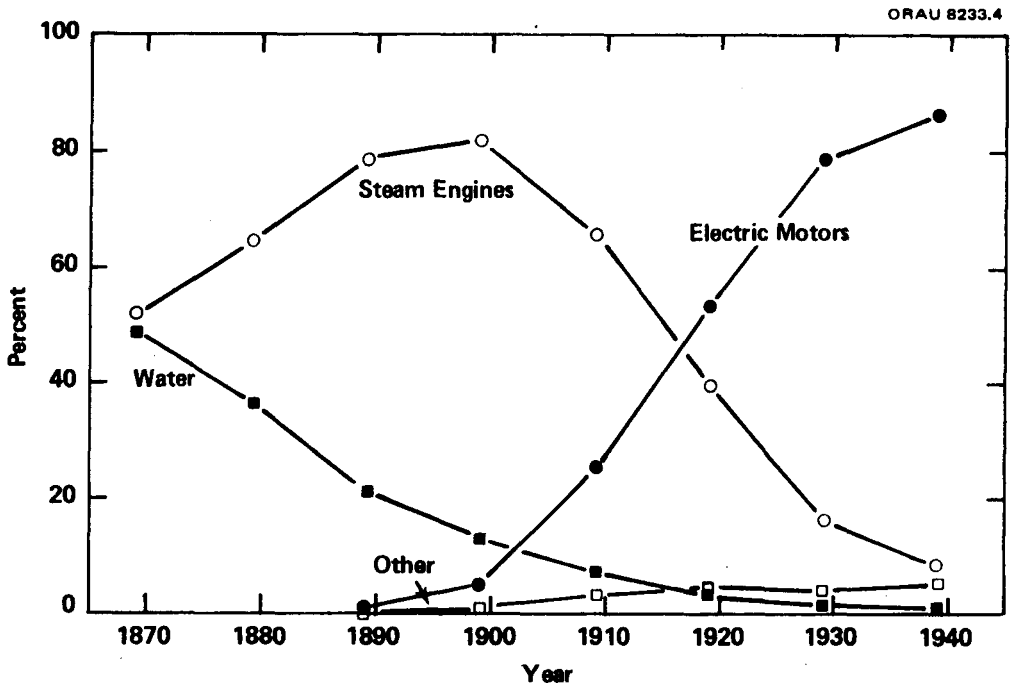

Figure 3. Sources of Mechanical Drive in Manufacturing Establishments, 1869-1939

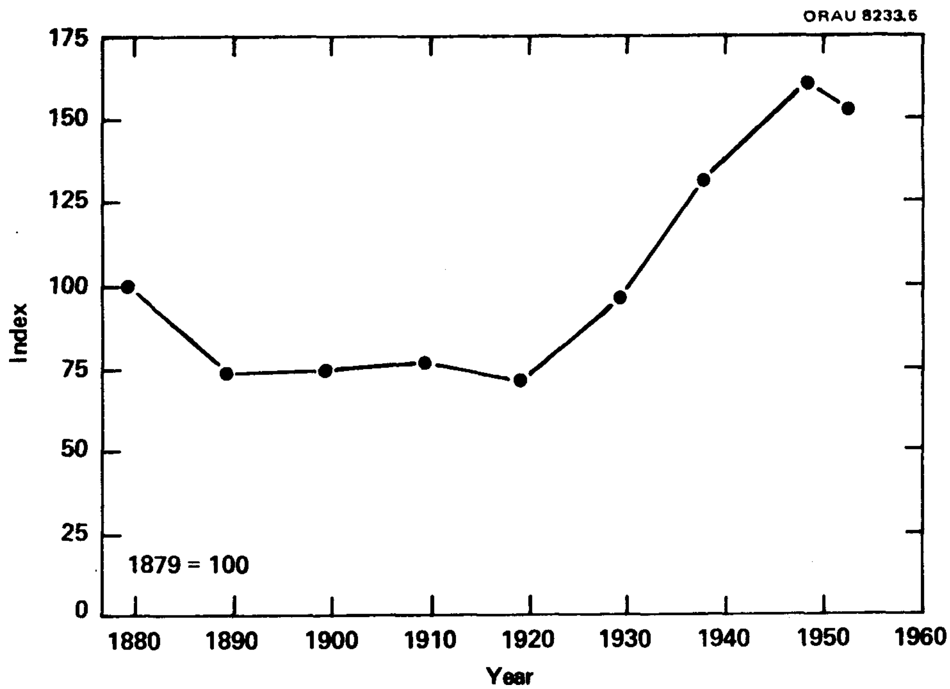

Figure 4. Total Mechanical Drive Power Capacity per Unit of Capital Input in Manufacturing, 1879-1953

engineers and economists present at the time of the transition. Such a view is presented in the following three sections.

III. LINE SHAFT DRIVE

DIRECT 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 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 5A.

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

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*A prime mover is a machine that converts the energy of falling water, steam, or fuels into mechanical power. Prime movers of interest in this paper are water wheels, water turbines, steam engines, steam turbines, and internal combustion engines.

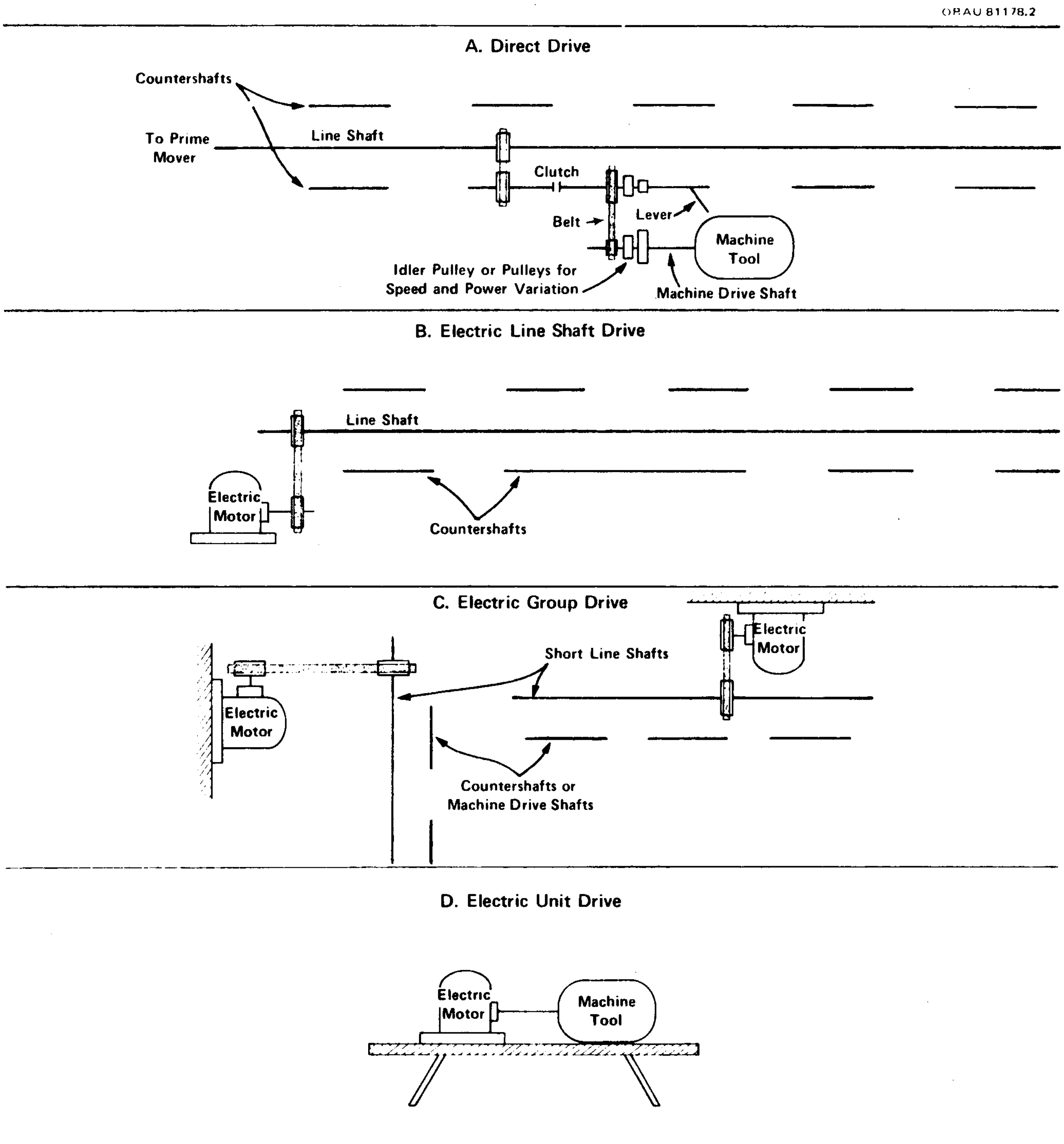

Figure 5. Evolution of Power Distribution in Manufacturing

plant often contained thousands of feet of shafting and belts and thousands of drip oilers.

ELECTRIC LINE SHAFT DRIVE

Electricity was probably first used for driving machinery in manufacturing in 1883 (14, p. 321)--the year after electric power was first marketed as a commodity by Thomas A. Edison. (A chronology of the electrification of American industry is given in Figure 6.) 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 were usually less than one horsepower (h.p.) capacity, and thus limited in application.

The first reliable and efficient d.c. motors in capacities exceeding one h.p. were developed by Frank Sprague, a former employee of Edison (15, pp. 238-40). 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 (16); 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 (13, p. 228).

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:

> The highest class of printing and engraving requires a steady and reliable power and one which is under the immediate and prompt control of the pressman. To secure perfect regularity and constant speed in addition to the above requirements many printers have adopted the electric motor in preference to other forms of power. The Sprague electric motors, because of their efficient regulation under varying loads, have met with great success in this class of work. The accompanying illustration [not provided] shows the press rooms of the Boston Bank Note and Lithograph Company, in which all the power used is supplied by a 10 h.p. electric motor. This is belted directly to the line of shafting running the length of the room, from

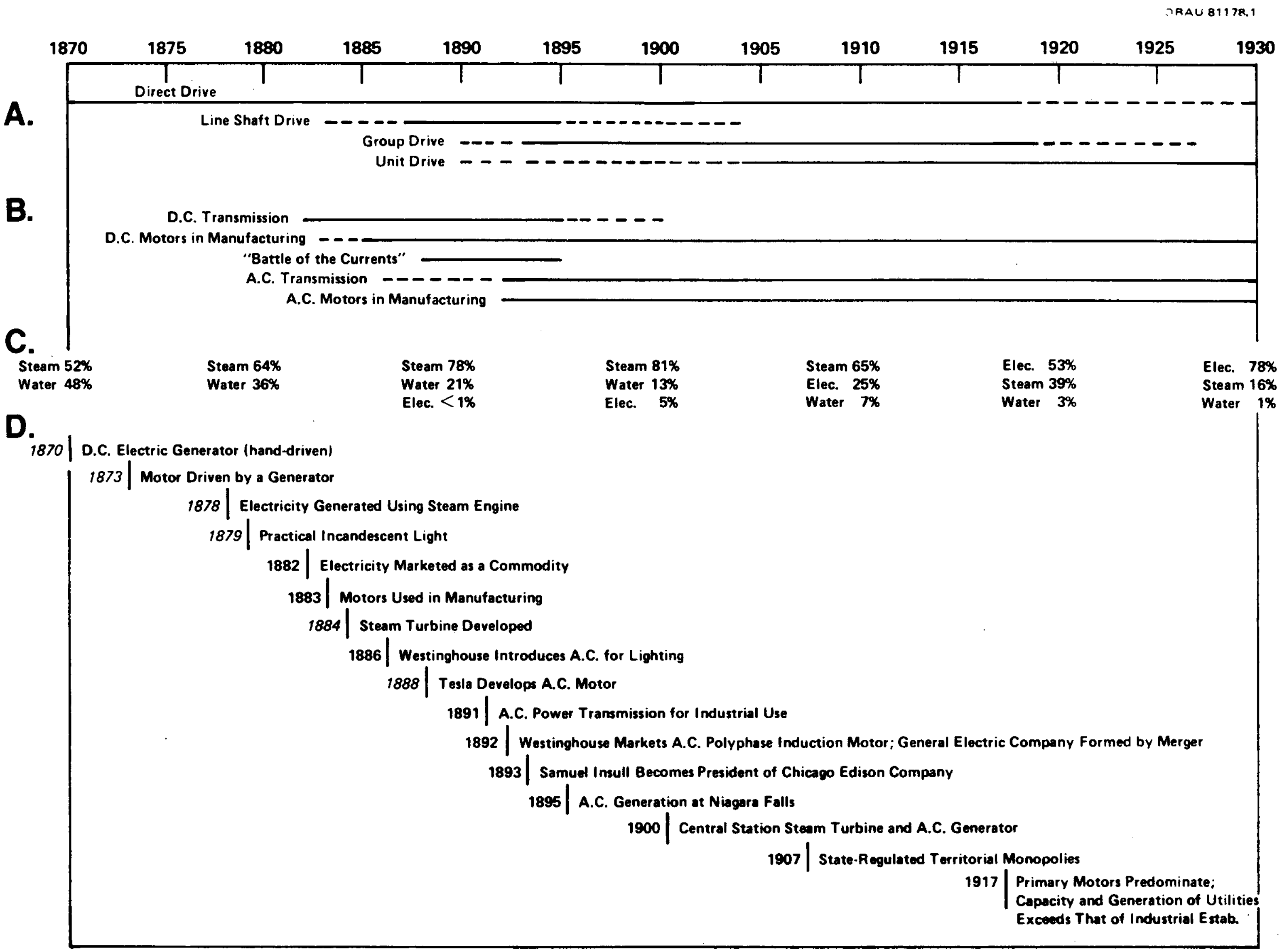

Figure 6. Chronology of Electrification of Industry. (A) Methods of Driving Machinery; (B) Rise of Alternating Current; (C) Share of Power for Mechanical Drive Provided by Steam, Water, Electricity; (D) Key Technical and Entrepreneurial Developments

> which are run the presses, folders, cutters, and other machinery used. Only a part of the presses are shown in the view, the shafting extending a considerable distance beyond the limits of the engraving. The motor occupies a space of less than 18 cubic feet, the engine for the same amount of work occupying from 10 to 15 times as much room (17).

As indicated in this 1890 account, electric motors may have improved the quality of work but did not change the method of providing power to machinery on factory floors. As illustrated in Figures 5A and 5B, 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; when small amounts of power were needed, it was usually cheaper to use electricity than steam. This was so because (1) small steam engines were much less energy efficient than large ones,* while the efficiency of electric motors varied little with size; and because (2) the price of small amounts of direct current electricity could be low if generated in large quantities in a central station. In a lecture delivered before the Franklin Institute, January 9, 1891, Dr. Louis Bell reported:

> Electric power [from a 1,000 h.p. steamplant] is much cheaper than using small steam engines at the places where the power is wanted, even allowing a large profit to the company that supplies the electricity—as a matter of everyday practice a common charge for running electric motors is $6 per horsepower per month; that is less than 25 cents a day. In taking out, then, a small steam engine and replacing it by an electric motor, there is gain at every point; at the price I have just mentioned, five horsepower could be bought for the daily wages of the man who would be required to look out for the engine and keep up the fire under the boiler (18).

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*Steam engines of 5-10 h.p. capacity typically consumed 7-10 pounds of coal per horsepowerhour while as little as 1.5 pounds were required for the same output by engines of 500-1000 h.p. capacity (18).

The "common charge" cited by Bell, approximately 2.5 cents per kilowatt-hour, is not, of course, the whole cost of mechanical drive as it does not include the cost of the motor and its maintenance. But the article indicates that electric line shaft drive--when the power required was on the order of tens or even hundreds of horsepower--was generally less expensive than direct drive with steam. This and other contemporary reports imply that electric drive was known to have certain benefits in production (cleanliness, ease of control, etc.), and that these benefits were factors in decisions to electrify. Yet comparisons of power sources were also made on cost-of-service grounds, with the service in this case being the turning of line shafts.

During the 1880s and early 1890s, 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,

> 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 (18).

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 (15, pp. 303-5).

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" (19, pp. 413-14). 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" (19, pp. 413-14).

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.

In summary, electric line shaft drive was employed because it had certain advantages in production and sometimes cost less than driving machinery directly. It was first used where low cost electric power was available--either in small quantities from the emerging electric utilities or in larger quantities from water power generators. Electricity was seen as a way to transmit mechanical power to factories, but not yet as an agent for distributing 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 '90s. 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

*When new technologies are introduced, the "system" in which they are used often retains, temporarily, elements of the old system being replaced; one might say there is no true system at first, but rather a hybrid of old and new technologies. Examples include railroad cars and stage coaches, steam ships and sailing vessels, automobiles and carriages.

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 (20). However, a number of older plants continued to use this method of driving machinery until the 1960s (21).

IV. ELECTRIC GROUP DRIVE

FROM TRANSMISSION TO DISTRIBUTION

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:

> Engineers will appreciate fully the tales the indicator will tell, in nine out of ten of our larger manufacturing plants, of the power devoted to revolving the immense 'main shaft,' and in transmitting power from one line of shafting to another when not a single machine tool is in operation (22, p. 12).

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. The purpose of a paper he presented to the 1891 meeting of the American Society of Mechanical Engineers was "to separate, so far as possible, the closely allied topics of power transmission and power distribution, electrically considered, and to treat the latter principally in the light of its adaptability to manufacturing and constructing operations" (22, p. 12). In the paper, Spaulding urged use of electricity, not long line shafts and interfloor belts, to distribute power to various points throughout the factory. 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 this system enable 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 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" (23).

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, pp. 303-5; 24). 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 (25, pp. 12-13). 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 5C). 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 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 (25, p. 13). 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 (26)! Obviously, the structural design and internal organization of these and other plants was 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, pp. 420-21). Some engineers even held "the extreme view . . . that a motor should be applied to every tool" (19, p. 417). Electric group drive is contrasted with direct drive and electric line shaft drive in Figure 5.

STEAM: DIRECT DRIVE OR ELECTRICITY?

From 1899 to 1909, electric drive increased from less than 5 percent of total capacity for driving machinery to 25 percent. During this decade only 30 to 40 percent of the electric motor capacity in manufacturing plants consisted of "primary motors"--i.e., motors driven by electricity purchased from an electric utility. "Secondary motors"--motors powered with electricity generated by the manufacturing establishments themselves--accounted for the majority of the capacity (Table 5 and Figure 7).

Table 6 and Figure 8 indicate trends in the way establishments generated the electric power that drove their secondary motors. In 1899, 85 percent of

TABLE 5. CAPACITY OF PRIMARY AND SECONDARY ELECTRIC MOTORS IN MANUFACTURING ESTABLISHMENTS, 1889-1954

(10^3 horsepower)

Year	Secondary Motors		Primary Motors
1889		16*	
1899	297		178
1904	1,089		428
1909	2,913		1,669
1914	4,684		3,707
1919	6,647		8,965
1925	9,976		15,116
1929	12,050		21,794
1939	16,011		28,816
1954	19,514		74,602

*No distinction made in statistics between secondary and primary motors.

Source: Reference 13, Table 13.

TABLE 6. CAPACITY OF PRIME MOVERS FOR DRIVING ELECTRIC GENERATORS IN MANUFACTURING ESTABLISHMENTS, 1889-1939

(10^3 horsepower)

Year	Steam Engines	Steam Turbines	Internal Combustion Engines	Water Wheels and Turbines	Total
1889	---	---	---	13	13
1899	24	---	13	218	255
1909	1,208	510	148	546	2,412
1919	1,855	2,634	367	794	5,650
1929	2,301	6,298	481	934	10,014
1939	2,250	9,537	870	1,208	13,865

Source: Estimates are based on reference 13, pp. 66-69, and Tables 14 and E-6.

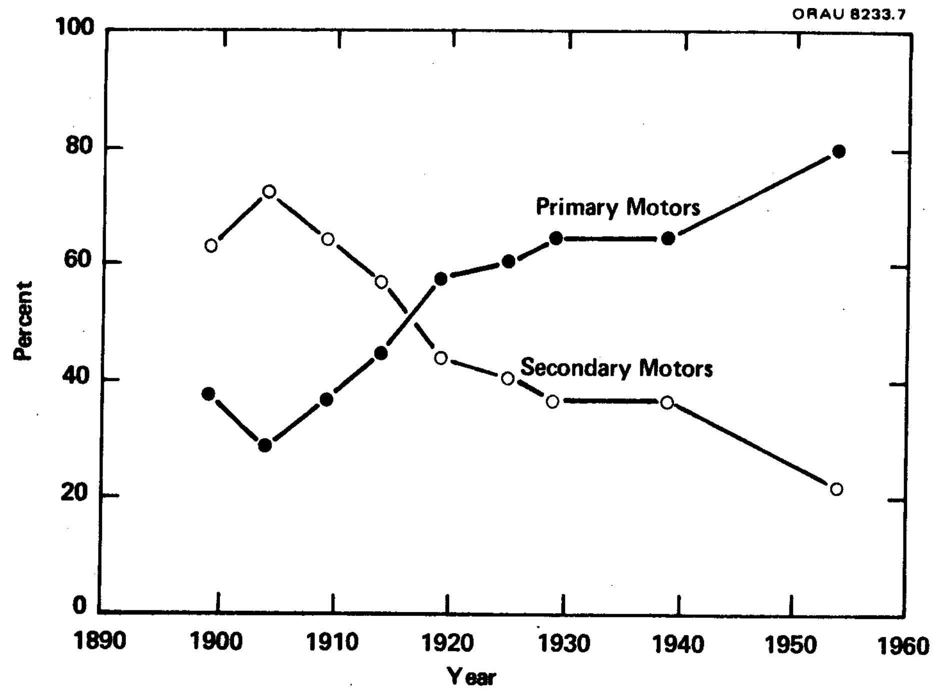

Figure 7. Primary and Secondary Electric Motors in Manufacturing Establishments, 1889-1954

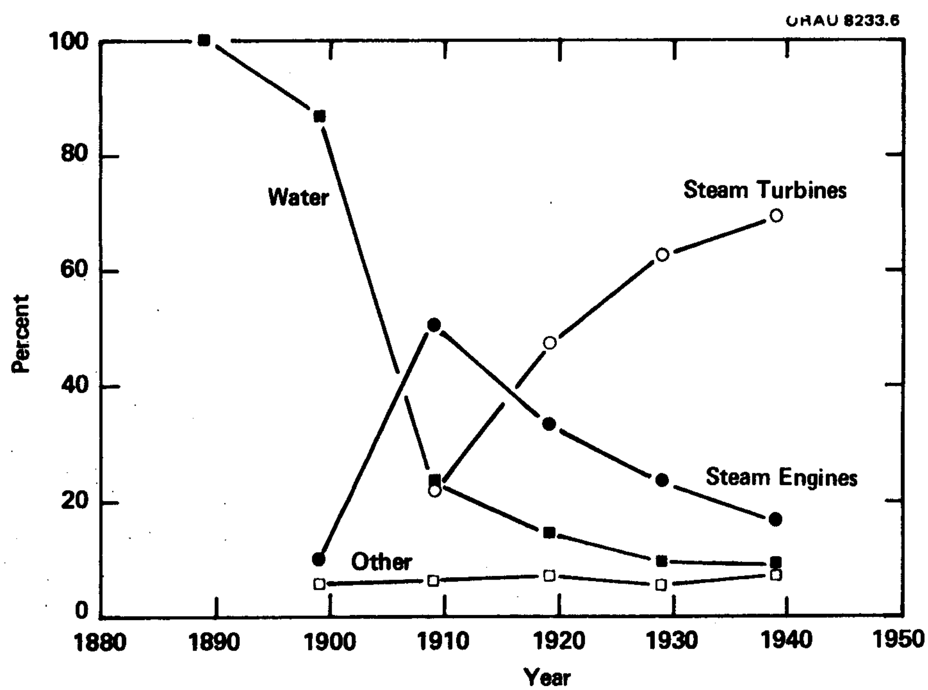

Figure 8. Prime Movers for Driving Electric Generators in Manufacturing Establishments, 1889-1939

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. In the following paragraphs we review some of the factors that led manufacturers to generate electricity with steam rather than to use steam directly for driving machinery.

It is not surprising that early adopters of electric group drive 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 (15, pp. 303-5; 27). With direct drive, loss between the steam engine and machines was at least 30 percent, and this only at optimum, full-load operation. On an efficiency basis alone, electric group drive based on hydro power was clearly preferable. 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. According to Professor Crocker:

> This stoppage in the case of the busiest tools, amounts to at least 25 percent of the nominal working hours throughout the year, and with large or special tools which are not used so steadily, the stoppage is often as high as 50 to 75 percent, since there are many whole days when they are not used at all (19, p. 415).

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. 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 (27-29; 30, pp. 6-7). There are a number of reasons for such a wide range of estimates.

First, friction loss did not vary much with load; but load was usually highly variable, with most machines operating at full capacity for only short periods of time. Thus, friction loss, expressed as a fraction of power made available, appears quite high at low loads and lower at high loads. Second, it was evidently difficult to keep shafting well lubricated and accurately aligned. Shaft hangers were often attached to the joists of the floor above and were deflected by shifting of weight upon the floor. Even the slight shaft deflections caused by excessively tight leather belts could lead to significant power loss. Finally, power loss in shafting depended upon the kind of machines being run, the length of shafting, the number of belts and pulleys. Textile manufacturer C. S. Hussey estimated that one horsepower was required to overcome the friction of 100 feet of 3-inch shafting rotating at 120 revolutions per minute (27). But this estimate included the associated countershafts typical of a cotton mill; friction loss in shafting of a metal fabricating shop might have been quite different.

One estimate of energy savings--due both to ability to operate groups of machines independently and to the reduction in shafting--was made by the Morris Safe Company of Readville, Massachusetts. The Company opened a new plant in 1895 in which they generated their own electricity for driving groups of machines. According to engineer G. W. Blodgett:

> This concern formerly operated by belting and shafting alone another shop where they were running about the same number of tools and doing the same kind of work, and they estimate a saving of 20 percent to 25 percent in the amount of coal used now over what it was when they ran entirely by belting and shafting (19, pp. 420-21).

One reason this company did not realize even greater energy savings in their new plant is undoubtedly the fact that there was still significant friction loss in the shafts and belts of electric group drive systems. In 1895, tests of the power required to drive various tools in different ways were described at a meeting of the American Institute of Electrical Engineers (AIEE)

(19, pp. 405-9). In one case, seven lathes and one grindstone were driven by a 3-h.p. motor via a short line shaft and countershafts. About one horsepower was required to turn the shafts--between 56 and 88 percent of the total power used, depending on the number of tools running. In another case, a large punch press and a planer were on a single shaft turned by a 7.5-h.p. motor; with only one of these tools in opration 47 percent of the total power used was required to overcome friction in the shafting.

Another reason that energy savings with group drive were not larger was electrical loss in generators, conductors, and motors. At full load, a power loss of 25 to 35 percent between a plant's steam engine and production machinery was typical (30, pp. 6-7). However, electrical loss--as a percentage of total power made available--did not increase with decreasing load as dramatically as did loss in long line shafts and countershafts. Although percentage loss in generators and motors is greater when partially loaded than when fully loaded, loss in conductors decreases as load decreases.

Thus, electric group drive did not necessarily entail dramatic energy savings as compared to direct drive based on steam. However, even large energy savings 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 (31; 32, pp. 2, 9; 33; 34, p. 890).

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 reorganization 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 installation of group drive, many manufacturers obtained reductions in fire insurance premiums

(29). 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 (23), of the Westinghouse plant in East Pittsburg (35), and of the seven-story building of the Kent and Stanley Company in Providence, Rhode Island [19, pp. 421-22].) These 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.

To summarize, electric group drive was first used by manufacturers of electrical equipment and by industries that located near sources of water power. In the late 1890s and early 1900s increasing numbers of firms began to drive groups of machines with electricity generated in their own steam plants. Electricity was now generally seen as a preferred method of power distribution within manufacturing plants: the factory reorganization that accompanied electrification brought significant benefits, and electric group drive was somewhat more energy efficient than direct drive. Group drive was a major form of electric drive through World War I and was vigorously defended as late as 1926 (34, p. 890). Yet even before the turn of the century, a few innovative manufacturers found it was best to elminate shafting altogether and run each machine with its own electric motor.

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V. ELECTRIC UNIT DRIVE

THE "EXTREME VIEW"

H. C. Spaulding, one of the first engineers to view electricity as a means of power distribution within factories, was intrigued by the "complete mechanical units" which could be formed if machines were driven individually by electric motors. Spaulding concluded the 1891 paper in which he forcefully advocated electric group drive by stating

> it is interesting to note the tendency to incorporate electric motors with various classes of machinery, thus forming complete mechanical units. It is to-day possible, for example, to equip a printing or publishing house equal in completeness to any now existing, without using a hanger, line shaft, or belt, each press being complete in itself as far as mechanical connection with the source of power is concerned, the entire transmission being accomplished by means of concealed wires (22, p. 13).

A few years later the presses in the U.S. Government Printing Office were driven in exactly this way. W. H. Tapley, chief electrician in the Office, reported in 1899 that

> the application of the [individual] electric motor to printing press machinery has produced results in power saved, improved product and increased output sufficient to cause every large printer today to look upon electrically-driven printing presses as a necessity and not a luxury (36, p. 259).

Nevertheless, 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 much less than the sum of the capacities required to drive each machine separately. According to Dr. C. E. Emery,

> Properly arranged groups therefore require a less number of motors, and motors of less aggregate power, and moreover the larger motors are proportionably cheaper so that a considerable saving of interest is secured to balance the comparatively small losses due to running short countershafts. These considerations are not arguments against the desirability of using independent

> motors on certain tools, but show the necessity . . . of considering the conditions for each particular case (19, p. 417).

Emery believed, however, that arguments in favor of applying a separate motor to each and every tool represented an "extreme view."

Technical societies between 1893 and 1904 frequently debated the relative merits of driving machines in groups or driving them individually. Most participants agreed with Dr. Emery: neither technique could be said to be best in all cases--the choice depended on the machine to be driven and on its use (37; 14, p. 348). 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 (14, p. 337).

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 5D). 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 (compare panel B with C and panel D with E of Table 7). More important, no energy was wasted turning shafts with some machines out of service. For example, in one careful test—performed at the U.S. Government Printing Office--0.553 watthours per impression were required when 13 presses were run in a group. Driven individually, each press required an average of 0.485 watthours per impression--a reduction of 12 percent due principally to elimination of

TABLE 7. REPRESENTATIVE FULL-LOAD EFFICIENCIES OF POWER PRODUCTION, TRANSMISSION, AND DISTRIBUTION IN MANUFACTURING, 1900-1920

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Boiler, Steam Turbine, Generator	Electric Power Transmission	Boiler and Steam Engine	Electric Generator	Electric Power Distribution	Motors	Mechanical Power Distribution	Overall
A. Direct drive							
		8-10% [a]				33-75%	3-8%
B. Self-generation and group drive							
		8-10%	92% [b]	92% [b]	77-90% [b]	50-75%	3-6%
C. Self-generation and unit drive							
		8-10%	92%	92%	77-90%		5-8%
D. Utility generation and group drive							
16% [c]	90%			92%	77-90%	50-75%	5-9%
E. Utility generation and unit drive							
16%	90%			92%	77-90%		10-12%

[a] Corresponds to 2-2.5 pounds coal per horsepowerhour. Source: Reference 38.
[b] Source: Reference 30, p. 6-7.
[c] Corresponds to 1.7 pounds coal per kilowatthour, typical of the Detroit Edison Company in 1922. Source: Reference 39, p. 426. This efficiency was somewhat higher than the national average.

friction loss. But the difference was more dramatic when only 5 out of 13 presses were run: over 0.83 watthours per impression were used with group drive, versus the same 0.485 watthours with unit drive (36, pp. 275-76). This additional saving of over 28 percent in energy consumption per unit of output was due mainly to elimination of idling loss.

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 (34, p. 890). 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 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 (30, p. 9). Nevertheless, the cost of equipping a plant with electric unit drive was usually somewhat higher than installing electric group drive (19, p. 414; 30, p. 8; 32, p. 2; 34, p. 892).

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. According to one manufacturer, "a good motor will require no adjustment for months at a time, and will then need only to have its brushes adjusted and its oil bearings filled. In the case of the polyphase motors, there are no brushes to attend to" (29). 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. 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 (19, p. 427).

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

> 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 (32, p. 8).

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*In recent times energy has represented approximately three-quarters of the total cost of driving production machinery (40).

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 (32, p. 9).

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 shared their experiences at technical society meetings.

> The great advantage of the electric system as here used [The Dunnel Cotton Manufacturing Company, Pawtucket, Rhode Island] is not so much in the saving of power as in the convenience to the workmen, and hence the increased production . . . the increase in the production amounted to more than 25 percent, and the quantity of "seconds" (inferior product) was also considerably reduced (19, pp. 412-13).

> Advantage to be gained from changing over from belting to individual electric motors for printing-press work is not alone in power saved, but . . . most of all, an increased product. Output of the Government Printing Office pressroom has been increased 15 percent . . . $45,000, a sum that makes the saving in motive power dwindle into insignificance. A few years will pay for the entire electric equipment, including the lighting (36, p. 278).

> . . . we have similar machines running side by side, one being operated by belt and the other by motor. The belt-driven machine has every advantage which we could give it . . . but experience would indicate that, under average working conditions, metal could be removed at least twice as fast as was originally possible (14, p. 329).

At one meeting Professor F. B. Crocker concluded:

> 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 (32, pp. 6-7).

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

Unit Drive Increased the Flow of Production in Factories

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" (32, p. 19). Furthermore, a machine's position could be 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 (19, p. 427).

Nine years later electric cranes were being called an "inestimable boon" to production (14, p. 337); by 1912, the importance of clear headroom for cranes was "so generally recognized as to require no comment" (30, p. 4).

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" (30, p. 4).

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.

Unit Drive Improved the 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 unit drive, and many observers felt this had a very positive impact upon the quantity and quality of work (19, pp. 429-30; 29; 30, p. 8; 32, p. 4).

Unit Drive 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 (41, pp. 2, 8, 10; 42). 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 (30, p. 5). 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 to conveniently 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 shunt-wound 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 could 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, 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 step toward the "ideal workshop"—a shop with a motor driving each tool or machine (32, pp. 24-28).

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 (14, p. 341).

Of course, the availability of relatively cheap induction motors and the alternating current to run them was 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.

Unit Drive Facilitated 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 (46). A number of these rapidly growing firms felt that mechanical power distribution systems imposed constraints on expansion of their plants (19, p. 428). With line shaft drive, the original power distribution system had to be designed with

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*In recent years, interest in variable speed electric drive systems has increased. Alternating current induction motors accounted for 85 percent of total motor capacity installed in industry in 1972; and around 85 percent of induction motor capacity consisted of motors of a single type: three-phase integral horsepower machines of squirrel-cage design (43). Fluid transport via pumps, compressors, blowers, and fans is a major application of these motors. With constant-speed drive, variation of flow or pressure of fluids is normally accomplished by throttling streams with valves--a method of control that can be quite inefficient. As fluid transport probably uses more electricity than other applications of industrial motors combined, an efficient, variable-speed a.c. motor drive system could yield significant energy savings. References 41, 44, and 45 describe the state of development of such systems in 1928, 1942, and 1981, respectively.

provision for expansion, or it had to be replaced entirely; ad hoc additions to the systems reduced efficiency and increased fluctuations in speed of driven machinery in the new parts of the plant (42; 32, pp. 5-6). 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 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 reasons for the Company's switch to electric unit drive (47).

In summary, during the 1890s and early 1900s, only the very largest machines were powered by individual electric motors. 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. With unit drive, electricity was used with its greatest economic advantage: processes could be arranged within factories to maximize throughput; plants could be more readily expanded; and a better working environment and improved machine control increased both quantity and quality of output. 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 was now viewed as a factor in improving overall productive efficiency.

VI. MARKET PENETRATION

The four methods of driving machinery that have been discussed in this paper were not necessarily employed consecutively by any firm. In fact, some manufacturers undoubtedly converted from direct drive to unit drive, skipping the intermediate stages. At any given time, all four methods of mechanical drive were probably in use. But the different techniques were most common during the years indicated by the time lines in Figure 6A. This figure 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 Figure 6A are based on four 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 (14, p. 348; 19, p. 411; 32, p. 23); neither technique could be said to be best in all cases. 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 (34, 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 (20; 41, pp. 8, 355).

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 (32, p. 8). 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 (14, pp. 333, 338). In 1904 several of the largest manufacturers of lathes adapted 30 percent of their product line for unit drive (14, p. 323). 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 (14, pp. 338-39).

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. However, progress toward the "complete re-design" of tools advocated by Duncan was not as rapid as he might have hoped. For example, in his 1928 textbook, Gordon Fox states

> There is a trend toward incorporating the motor as an integral part of the machine tool. A number of machines have been developed with the motor mounted in the pedestal, housing, or on the frame in the rear of the machine. . . . In numerous cases it has proven advantageous to carry the individual drive to the extent of a subdivision of mechanisms of a single machine with an individual motor applied to each element (41, pp. 12, 356).

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 (Figure 3). 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 site; ten years later 57 percent of the capacity was driven by electricity purchased from electric utilities (Figure 7). 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 (Table 8 and Figure 9).

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 (15, pp. 310-13). The use of turbines grew rapidly, achieving predominance around 1917, largely at the expense of steam engines (Table 9 and Figure 10).

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 (48). 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 (14, pp. 323-26, 340-41). 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 (39, pp. 159-60). 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.

TABLE 8. ELECTRIC GENERATING CAPACITY IN UTILITIES AND OTHER ESTABLISHMENTS, 1889-1954

(megawatts)

Year	Manufacturing Establishments	Nonmanufacturing Industrial Establishments*	Electric Utilities	Total
1889	10	102	89	201
1899	190	835	895	1,920
1902	482	1,292	1,211	2,985
1907	1,350	2,748	2,708	6,806
1912	2,485	3,327	5,163	10,975
1917	3,705	2,792	8,990	15,487
1920	4,538	2,184	12,709	19,431
1925	6,218	2,394	21,463	30,075
1929	7,467	1,398	29,828	38,693
1939	10,339	244	38,847	49,430
1954	15,590	690	102,551	118,831

*Railroads, mines, farms, and "services."

Source: Reference 13, Table E-1.

TABLE 9. CAPACITY OF PRIME MOVERS IN ELECTRIC UTILITIES, 1902-1952

(megawatts)

Year	Steam Engines	Steam Turbines	Internal Combustion Engines	Water Wheels and Turbines	Total
1902	797	119	8	287	1,211
1907	1,240	542	35	891	2,708
1912	1,301	2,096	78	1,688	5,163
1917	1,186	4,693	144	2,967	8,990
1922	979	8,824	213	4,170	14,186
1927	702	17,072	376	6,919	25,069
1932	481	23,580	619	9,693	34,373
1937	463	24,034	783	10,326	35,606
1942	---	31,164	1,036	12,835	45,035
1947	---	36,035	1,308	14,958	52,301
1952	---	59,673	2,137	20,384	82,194

Source: Reference 13, Table E-3.

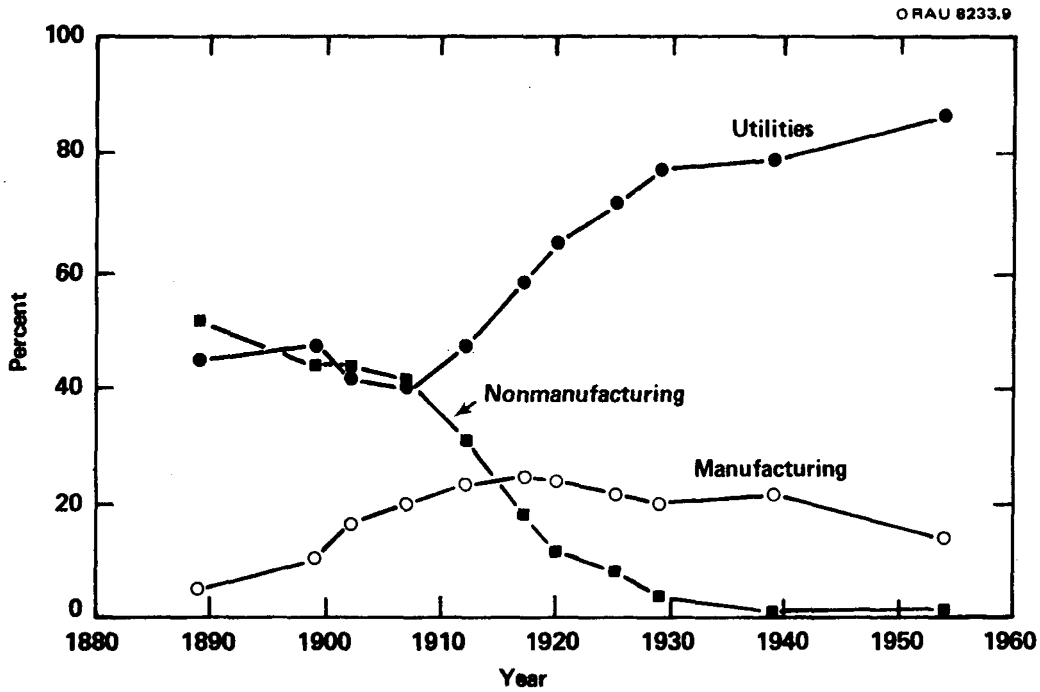

Figure 9. Electric Generating Capacity in Utilities and Other Establishments, 1889-1954

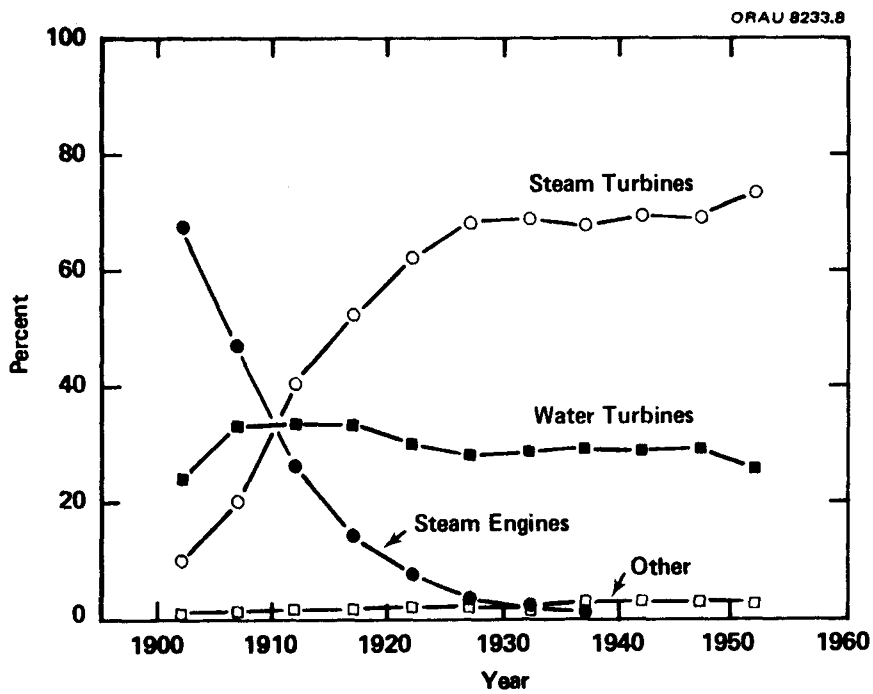

Figure 10. Prime Movers in Electric Utilities, 1902-1952

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 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 (39, pp. 159-60). 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.

Fourth and finally, the continuous decline in average capacity of installed electric motors reflects the trend toward unit drive. It has been noted that motors driving groups of machines were generally larger than motors driving individual machines. Group drive was most common over the same period that secondary motors were predominant. Therefore, secondary motors must have been larger—on the average—than primary motors; Table 10 and Figure 11 illustrate that this was indeed the case. But the changes in average motor size over time are perhaps more noteworthy. The steady decrease in average capacity of secondary motors may reflect the shift from large motors for turning long line shafts to smaller motors for driving machines arranged in groups. Furthermore, the relatively constant average capacity of primary motors followed by declining capacity after 1919 could reflect a shift from use of primary motors for both group and unit drive toward exclusive use for unit drive.

To summarize, after the introduction of the a.c. motor and the steam turbine, unit drive and utility electricity began to displace other modes of driving machinery. But group drive was still advocated for many applications, and it took time for machines designed around motors to come into common usage. Nevertheless, electric unit drive was increasingly installed in new facilities, and sometime after World War I it supplanted other methods of driving machinery.

TABLE 10. AVERAGE CAPACITY OF ELECTRIC MOTORS IN MANUFACTURING ESTABLISHMENTS, 1899-1939

(horsepower)

Year	Secondary Motors	Primary Motors
1899	18.2	---
1904	15.7	---
1909	16.1	8.6
1914	15.3	8.5
1919	14.3	9.3
1925	13.2	9.0
1929	14.5	8.2
1939	13.1	7.1

Source: Reference 13, Table 19.

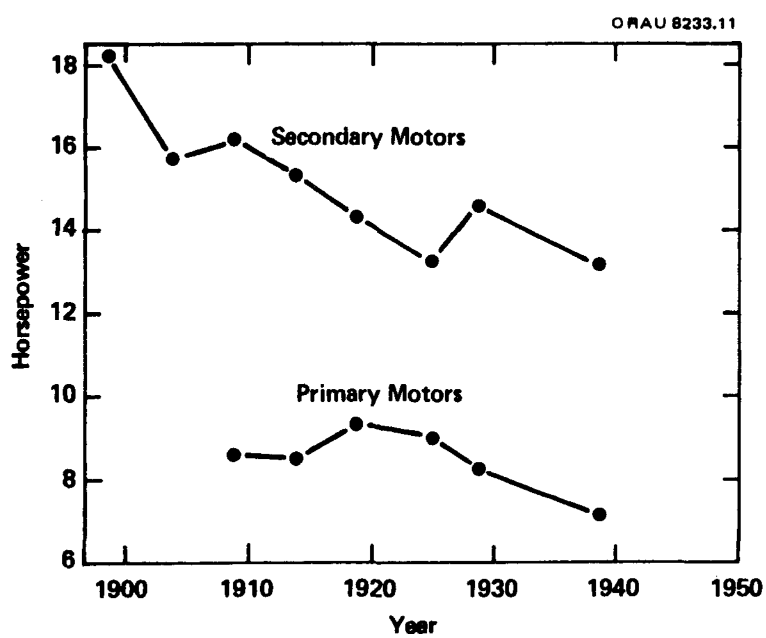

Figure 11. Average Capacity of Electric Motors in Manufacturing Establishments, 1899-1939

VII. SUMMARY AND CONCLUSIONS

REVIEWING THE REVOLUTION

Electric drive evolved over a 40 to 50 year period, between approximately 1880 and 1930. Previously-displayed figures reflecting changes in electricity use and production during these years are brought together in Figure 12 to re-emphasize that extremely rapid and all-pervasive change immediately following World War I.

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 (Figures 12A, B, and C). Efficiencies in production made possible by unit drive are manifest in significant increases in the productivity of labor and capital beginning just after World War I (Figure 12D). The shift to the utility sector of resources used in electricity generation contributed to these productivity increases and also to the sharp rise in power capacity per unit of capital input in manufacturing (Figure 12E). However, a more important reason for this latter upswing is that unit drive required several times as much motor capacity as other forms of electric drive. Finally, it is clear that unit drive used less energy per unit of output than other methods of driving machinery. Nevertheless, there is strong evidence that the expanded output in manufacturing made possible by unit drive also contributed—in an important way—to the dramatic change in trend of the energy-GNP ratio around 1920 (Figure 12F).

THE "FORM VALUE" OF ELECTRICITY

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 (47, 49, 50).

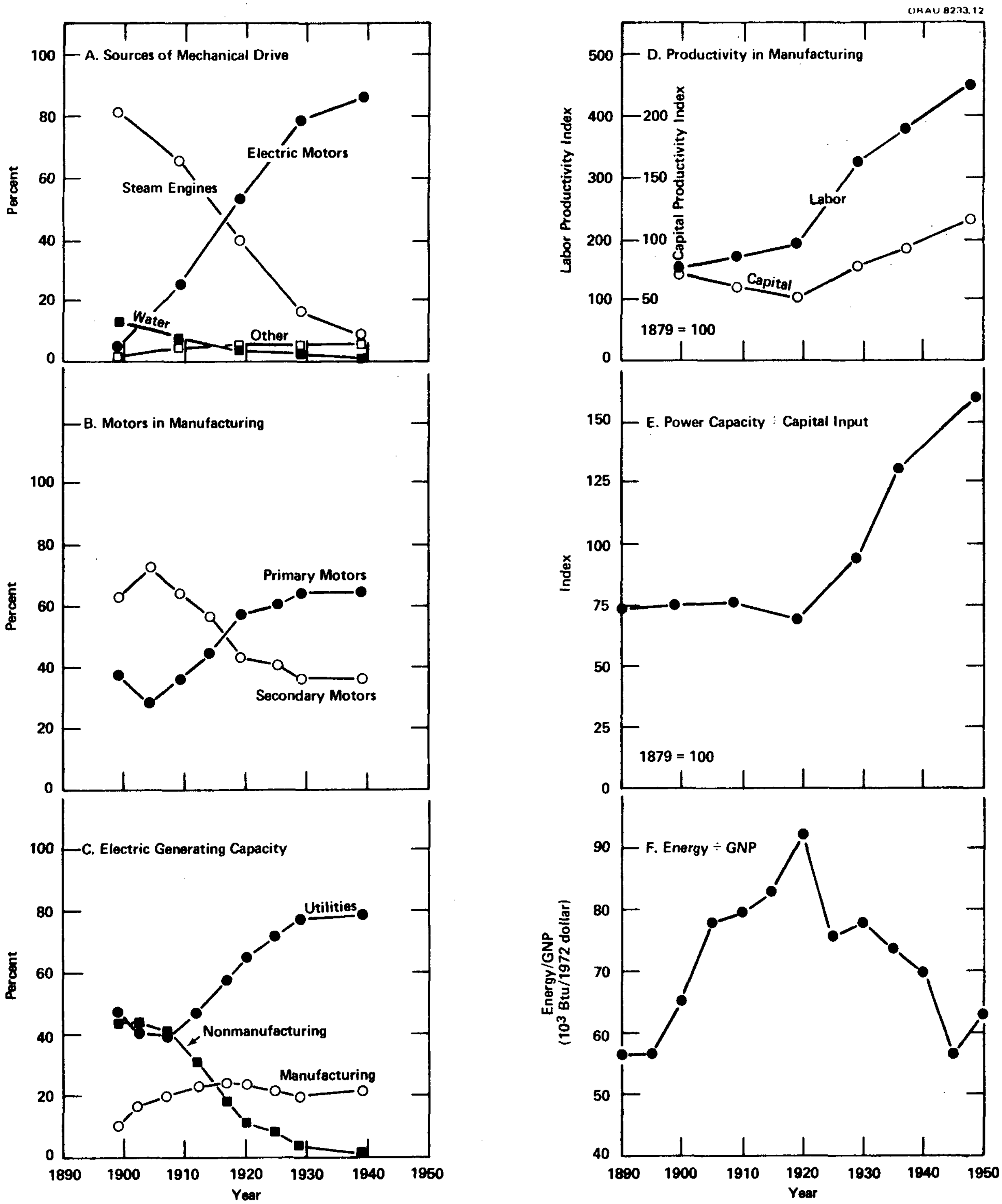

Figure 12. Evidence of Revolution

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. For example, electric 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--i.e., 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.

REDEFINING THE ENERGY SERVICE

The term "energy service" sometimes refers to one of several tasks accomplished through the conversion or transfer of energy: for example, heating rooms, raising the temperature of materials during manufacturing, and driving machines (40, 51).

In Section III we noted that during the 1890s many firms replaced their central steam engine with large electric motors, leaving the mechanical power distribution system essentially unchanged. In effect, the energy service sought was the turning of line shafts. In seeking only to provide this service at minimum cost, they failed to exploit the precision with which energy in the form of electricity could be transferred. Later, the energy service was--in effect—redefined to be the turning of machine drive shafts. As we have seen, the difference in cost of providing this service was of little consequence compared to the leverage electric unit drive exerted in production.

But the turning of machine drive shafts is no more a fundamental energy service than was the turning of line shafts. Machines are driven, after all, to bring about some change in the physical properties of materials--for example, the removal of metal from a workpiece, or machining. Although this physical change is usually accomplished mechanically, in some instances it may also be done electrochemically—i.e., with virtually no use of mechanical drive (52). Use of electrochemical machining could have significant impact on productivity in many industries.

Thus both history and on-going technical progress warn us against paying undue attention to the relatively narrow goal of minimizing the cost of an energy service, however it may be defined. Such an approach could divert us from seeking other ways of bringing about desired physical or chemical transformations--ways which, like electric unit drive, could exert great leverage in production.

INNOVATION AND ELECTRIFICATION

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 factories. Two years later, General Electric salesman S. B. Paine demonstrated that electricity could be used to benefit production in more indirect ways as well. And beginning in 1895, a series of discussions led by Professor F. B. Crocker all but confirmed the innovative 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 rise of electric drive was fostered by innovation in the supply of electricity as well as in the use of it. By implementing policies that increased demand—for example, consolidation of small systems and marketing complete energy services--utilities reaped economies of scale inherent in the new steam turbine power plants. This kept the cost of electricity low, encouraging further electrification and the dismantling of industrial electric power plants.

It is apparent, therefore, that the first major shift to electricity in manufacturing was characterized by changes in the perceived role of electricity and by technical and entrepreneurial innovation. If there is to be a second shift--this time from the use of fuels to the use of electricity for process heat—it seems reasonable to expect that analogous developments will be required. Specifically, advocates of electrification will have to show that electric heating processes increase productive efficiency and in so doing reduce overall energy use and the cost of heat. Electric utilities will have to ensure that electricity will be available as needed and on favorable terms. And manufacturers, utilities, and suppliers of electrical equipment will have to work together in integrating new electric technologies into production.

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