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Gains from Factory Electrification: Evidence from North Carolina, 1905-1926*

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Abstract

Between 1900 and 1930, the share of power in American manufacturing coming from electricity grew from 10% to 80%. Although electrification has been attributed with dramatic productivity gains, data limitations have constrained previous research to rely on aggregate data. Using a newly-collected dataset covering manufacturers in North Carolina in the early 1900s, I examine the effects of electrification at the establishment level. Manufacturers who electrified increased their productivity and output relative to manufacturers who did not. The effects on workers were mixed. While electrification increased average wages, it also increased the return to skill and reduced the labor share. Delays in electricity adoption point to the importance of complementary innovations in electricity transmission and financial markets.

One of the key innovations of the Second Industrial Revolution, electrification transformed life around the turn of the twentieth century. The impact of electrification was especially visible in the manufacturing sector, where electricity replaced water and steam as a power source, providing 80% of power by 1930.[1] Economists such as Robert Gordon (2000) and Paul David and Gavin Wright (1999) have highlighted the importance of electricity for the rapid growth of manufacturing productivity in the early twentieth century. However, due to the destruction of the manuscript records for the Census of Manufacturing, a lack of establishment-level manufacturing data has made it difficult to quantify how the adoption of electricity affected factories and workers.

In this paper, I study the gains from electrification and the effects on workers using a new dataset covering North Carolina manufacturers between 1905 and 1926. The data,

[1] See Figure 1.

collected from reports published by the state's Department of Labor and Printing, provide detailed factory-level information on revenue, employment, capital, and energy use. Few sources of establishment-level data exist for this period, so this dataset helps fill a gap in which Census microdata is not available.[2] Electricity usage in North Carolina followed a similar trend to the rest of the country, though the share of energy coming electricity was slightly lower in the state than the country as a whole between 1900 and 1930.[3]

I use this data to address three key questions. First, I quantify the productivity gains from electrification and test the contributions of various mechanisms. Second, I study the effect of electrification on workers and highlight electricity as an early case of skill-biased technical change. Last, I ask why many manufacturers did not electrify, despite the large gains from adoption, and highlight the role of finance and infrastructure in technology diffusion.

Because I observe individual establishments, I can directly compare factories using electricity to those using other sources of power. However, electrification is endogenous. Factories that electrified may have been able to do so because they were more productive. To address the endogeneity, I use two different approaches. For the textile sector, I link factories through time, creating an establishment-level panel. I then control for factory fixed effects to capture factory-specific characteristics that might have influenced both productivity and the likelihood of electrifying. For factories in other sectors, inconsistencies in naming patterns make it difficult to link establishments through time. For these factories, I use two different approaches. I include a wide variety of controls to capture selection into electrification on observables. I also use analyze the linked factories using a difference-in-differences approach and find similar results.

[2]For periods in which microdata from the Census of manufacturers exists, economists have used it to answer important questions. See Atack and Bateman (1999) for a discussion of Census data from 1850-1880 and Vickers and Ziebarth (2015) for a discussion of the Great Depression samples for 1929-1935. Unfortunately, the Census data for the intermediate period has been destroyed.

[3]Appendix Figure A.1 compares electricity usage in North Carolina to the country, a New England textile state (Massachusetts), and another southern textile state (South Carolina). These states followed similar trends to national electricity usage.

First, I show that electricity did in fact provide large benefits to manufacturers, increasing both output and productivity. Electrifying manufacturers adopted production processes that were more capital- and energy-intensive, though the added capital and energy explain relatively little of the increase in output per worker. I also rule out certain proposed benefits of electrification by showing that manufacturers did not upgrade their products when they electrified or take advantage of more flexible scheduling by running night shifts.

Second, I show that electrification increased the average wages paid by a factory. However, wage gains were not universal: the best-paid workers within factories saw larger gains than those at the bottom of the wage distribution. The labor share of output also decreased, reflecting the increased capital investment. These patterns are consistent with electricity allowing manufacturers to substitute capital and energy for unskilled labor.

Given that electricity provided large gains, why didn't everyone electrify? I conclude by documenting how the costs of electrification slowed the diffusion process. First, I show that steam-powered factories were more likely to electrify than those using water-power, highlighting the role of sunk investments in existing technologies. Second, I show that factories owned by corporations were more likely to electrify than those owned by partnerships or individuals, suggesting that capital constraints may have prevented firms from paying the costs of electrification. Third, I show that factories located near a hydropower plant were more likely to electrify, though the effect was limited to plants within 30 km of a hydropower site, demonstrating the need for the development of the electric grid to allow widespread electrification far from power plants.

This paper contributes to a large literature on the productivity effects of electrification. Economic historians have attributed large productivity gains to electricity, with papers by Paul David (1990) and Bakker et al. (2019) using growth accounting techniques to attribute between a quarter and half of the growth in U.S. manufacturing TFP between 1919 and 1929 to electrification. A recent working paper by Fiszbein et al. (2022) uses aggregate data at the city-industry level to show factories in energy-intensive sectors located near hydropower plants increased their productivity and capital intensity. Although many papers have studied the effects of electrification in modern developing countries (see, for example, Dinkelman (2011)), estimates from a development context are unlikely to be directly applicable as electrical technology has changed dramatically over the past hundred years. My paper contributes to this literature by estimating the gains from electricity at the plant level and testing various mechanisms through which electricity could have mattered.

Second, this paper contributes to a literature on the labor market effects of technology adoption. Past research has highlighted that the effects of electrification on workers differed by skill and occupation. Goldin and Katz (1998) argued that electrification was complementary to skill, proxied by education, while Gray (2013) found that electricity increased the demand for clerical and manual occupations while reducing the demand for skilled blue-collar jobs. Drawing out the implications of these effects, Gaggl et al. (2021) found that electrification contributed to structural change by shifting workers out of agriculture while Vidart (2022) argued that electrification increased the labor force participation rate of skilled women by increasing the skill premium. My paper builds on this literature by documenting that electrified manufacturers in fact paid higher wages on average than non-electrified manufacturers. By providing direct evidence on wages, I complement alternative measures based on occupation or education-levels which may be a coarse measure of the relevant skills (David and Wright 1999). I also show that wages increased for the best-paid women, which shows that the electrification had broad effects on workers and did not simply involve hiring a small group of skilled men for tasks such as machine maintenance.

Third, this paper contributes to the literature on the general purpose technologies. Although economists have debated the concept of a general purpose technology, almost every list includes steam, electricity, and information and communications technology (ICT).[4] Despite the importance of GPTs, they often take a long time to be adopted throughout the economy. Economists have suggested a variety of reasons for slow electrification, such as the need to learn how to use a new technology (Atkeson and Kehoe 2007), unsuitable technology (Goldfarb 2005), the cost of purchased electricity (Woolf 1984), or the challenge of electrifying established factories (David and Wright 2006). This paper highlights the role of imperfect capital markets and a limited electric grid in slowing adoption. These examples also suggest issues that may slow contemporary technology diffusion.

The paper proceeds as follows. Section 1 reviews the history of factory electrification. Section 2 describes the dataset. Section 3 presents the empirical approach. Sections 4 and 5 demonstrate the effects of electrification on productivity and wages, respectively. Section 6 discusses the decision to electrify. Section 7 concludes.

1 History of Electrification

During the early twentieth century, manufacturers replaced water and steam with electricity. As shown in Figure 1, electricity accounted for less than ten percent of horsepower used in US manufacturing in 1900 but provided almost 80 percent of manufacturing power by 1930.[5]

Electricity provided manufacturers with a variety of benefits (Gray and Kitchens 2018). For example, electric lighting replaced gas lighting because it was cleaner and safer. Electricity also reduced energy costs because it could be generated at a low-cost site, such as a hydropower plant or a large steam-powered plant, then transmitted to a factory where the electricity could be used to power machines.[6]

[4]See Field (2008) and Jovanovic and Rousseau (2005) for discussions of the GPT paradigm.

[5]Electrification spread faster in manufacturing than in other sectors; only 10 percent of farms were electrified by 1930 (Lewis and Severnini 2020).

[6]Devine (1983) estimated that energy accounted for only 0.5-3% of total production costs, so these direct cost savings were likely of secondary importance.

The more dramatic effects of electrification came from changes in how power could be transmitted within a factory. Before electrification, manufacturers generated power using steam or water and transmitted it through the factory using a complex system of belts and shafts. After electrification, manufacturers instead transmitted power using wires.

The ability to power each machine individually allowed manufacturers to reorganize factories.[7] Because energy needs no longer constrained where machines were located, manufacturers could arrange machines so that materials moved linearly through the factory without having to backtrack to previous stages of production. Electricity also allowed manufacturers to operate a subset of machines, making it more convenient to operate multiple shifts or shut down part of the factory for repairs or adjustments. These changes had direct implications for workers, as described by David and Wright (1999). By reorganizing factories, manufacturers saved on unskilled labor for material handling.[8] Manufacturers who adopted electricity highlighted these benefits. Henry Ford declared "The provision of a whole new system of electric generation emancipated industry from the leather belt and line shaft, for it eventually became possible to provide each tool with its own electric motor... In fact, modern industry could not be carried on with the belt and line shaft" (quoted in Nye 1998).

1.1 Comparison to Steam

The prior transition from water to steam provides a useful comparison. Economists have highlighted the importance of the steam engine for manufacturing in the nineteenth century, and several recent papers have used microdata to study the effects of steam adoption (Hornbeck et al. (2024), Atack, Bateman, and Margo (2008)).

Steam provided a variety of benefits. By freeing factories from a reliance on water-power, it encouraged year-round operation and made it possible to locate factories away

[7] Du Boff (1967) and Devine (1983) provide detailed case studies of factory electrification.

[8] Jerome (1934) estimated that handling accounted for over 20% of the average factory's wage bill.

from rivers. Atack, Bateman, and Margo (2008) find that manufacturers using steam were more labor-productive than others, though they argue that most of the benefits of steam came from increased size and division of labor, rather than fundamental differences between water and steam. Despite these benefits, Hornbeck et al. (2024) find that steam diffused slowly, highlighting the importance of switching costs and the sunk investments in waterpower.

Steam and electricity have been frequently compared, especially with regard to their impact on workers. Goldin and Katz (1998) suggested that steam may have substituted for skill, as it allowed a switch from artisanal production to factories. Katz and Margo (2014), however, suggest that the effects of steam may have been a bit more complicated, hollowing out the skill distribution as it both allowed less-skilled workers to replace artisans and required the hiring of white-collar managers and skilled engineers.

In this paper, I find evidence that electrification was a case of skill-biased technical change, in contrast to the more complicated effects of steam, though the productivity gains are comparable. One important difference is that the changes in energy transmission made possible by electrification allowed factories to reconfigure work processes, where steam adoption primarily involved changes in energy generation. The shift from artisanal to factory production associated with the steam era likely mattered more, rather than the specific type of power used within the factory.

2 Data

The primary source of data in this paper is a factory-level data set covering North Carolina manufacturers between 1905 and 1926 collected from reports published by the state's Department of Labor and Printing.[9] Though the reports began in 1887, inconsistencies

[9] Early reports were published as the Bureau of Labor Statistics. I use the title Department of Labor and Printing throughout for consistency.

in the structure of the early reports before 1905 make them unusable.[10] Appendix A provides a more detailed discussion of the data.

Comparing the microdata to aggregate data from the US Census of Manufacturing shows that the reports accurately described the North Carolina economy. Appendix Tables A.4-A.6 report comparisons for the cotton textile industry between the North Carolina data and aggregate data as reported in Census publications for 1909, 1914, and 1919. The North Carolina data actually includes slightly more establishments than the aggregate data for North Carolina, likely reflecting differences in how industries were classified. Average factory sizes in both data sets are quite close, though some of the largest factories may have chosen not to report the value of their output to the Department of Labor. Overall, this comparison suggests that the North Carolina reports accurately describe the North Carolina textile industry.[11]

The reports include detailed information on each factory, including information on labor force composition, wages, power use, location, and value of output, though the exact questions asked varied across years. For example, manufacturers were not asked for the value of their output until 1912. Appendix Table A.2 describes the questions asked for each year and industry. The reports for the textile sector provide information on physical capital, counting the number of spindles at each factory, but limited information on wages while the reports on other industries report the total wage bill. Due to these differences in the structure of the original reports, I work with two separate datasets. First, I have collected a panel dataset for textile manufacturers between 1905 and 1926. Second, I have collected a dataset for "miscellaneous factories," which includes manufacturers in industries other than textiles and furniture between 1915 and 1926.

[10] Due to the number of questions asked, the reports split the data across multiple tables. Unfortunately, the tables in the early reports are numbered inconsistently and only the first table includes plant names, so it is not possible to link manufacturers across different tables within the same report.

[11] Unfortunately, differences in how electrification is measured make it impossible to compare between the two datasets. The Census reports electrification as the share of horsepower coming from electricity, while the North Carolina reports indicate whether or not a factory is electrified.

2.1 Cotton Mill Panel

This data set includes 5426 establishment-year observations covering 714 unique establishments.[12] Appendix Table A.1 reports summary statistics for key variables.[13] Cotton mills were a major component of the manufacturing sector in North Carolina. In 1919, for example, 43% of the industrial labor force in North Carolina worked in cotton textiles (Galenson 1985, p. 9).

The reports asked each factory for the number of horsepower available as well as the sources of power used. Some plants reported using multiple sources of power, though the reports do not break down how much power each source provided.[14] Figure 2 illustrates the share of establishments using each source of power in each report year - note that, because manufacturers were able to report multiple sources, the totals sum to over 1. This figure illustrates the replacement of steam power by electricity during this period. In 1905, 5% of textile producers were using electricity and 82% were using steam; by 1926, 83% were using electricity while only 17% continued to use steam.[15]

2.2 Miscellaneous Factories

I have collected the data for "miscellaneous factories", which includes factories not listed under cotton mills, knitting mills, furniture, or tobacco, for the years between 1915 and 1926.[16] This dataset consists of 15,738 observations. This dataset includes information

[12] See Appendix A.2 for a description of how factories were linked across reports.

[13] Appendix Table A.3 reports the number of observations in each report year. Over this period, many new cotton mills entered as the industry moved to the South (Galenson 1985, Wright 1986).

[14] 72% of establishments report a single power source, 23% report two, 2% report three, and 2% do not report their source of power.

[15] The first all-electric mill was the Columbia Cotton Mill in South Carolina which used electricity to transmit power from a nearby river and began operating in 1894 (Bonham 1979). Within North Carolina, the Southern Power Company specifically marketed their electricity to textile manufacturers by investing in southern cotton mills, beginning in 1905 (Durden 2001, p. 20-22).

[16] Although furniture and tobacco were important industries in the state, the reports for these industries include less data than either the textile or miscellaneous reports.

on the total wage bill, which the reports did not collect for the textile sector.

For most of my analysis using these miscellaneous factories, I do not link factories through time. The reports note greater difficulties in collecting data from all manufacturers in this section, so this is not a full census of manufacturers. In addition, many of the small enterprises have names which make it difficult to identify manufacturers uniquely across time; for example, reporting under the owner's name or simply their town and type of business. In Appendix A.2, I discuss the difficulties in linking these factories through time. Manufacturers do not necessarily report under the same name across years. For example, the same manufacturer is reported as "Jug Town" in 1915 and "W. M. Penland" in 1918. I am able to link these factories only because this plant is well-documented in other sources - there are likely similar matches which lack outside evidence for me to make a certain match. In Section 5.4, I find qualitatively similar, but slightly smaller, results when I use a set of factories linked between 1915 and 1920.

3 Empirical Approach

The empirical approach in this paper moves through three steps. First, I show that electrification provided manufacturers with large increases in productivity. Second, I show that some, though not all, of the productivity gains were passed on to workers in the form of higher wages. Third, I show that the costs of adoption delayed electrification, despite the large potential for productivity growth.

Within the textile sector, I find that on average electrified cotton mills were 12% more productive than non-electrified mills. However, electrification was a choice. For example, manufacturers with more talented management may have been more productive and also more likely to adopt the newest technology. I use several approaches to address endogenous electrification.

Using the panel of cotton mills, I present fixed-effects regressions and identify the effect of electrification using variation in the timing of adoption. Establishment-level fixed effects capture unobservable characteristics that might have driven selection into electrification.

For other industries, difficulties in linking factories through time complicate a fixed-effects approach. To address endogeneity concerns, I control for factory characteristics and show that these variables do not explain the electrification premium. I also use a difference-in-differences approach with the factories I am able to match and find similar results. In Appendix Section D, I discuss attempts to identify a valid instrumental variable and explain limitations of this approach.

Because I do not observe the costs of electrification directly, I use several different approaches to show that adoption costs were relevant. First, using the panel of cotton mills, I document factory characteristics related to adoption timing. Second, using the data from other industries, I test whether electrification was related to the location of hydropower and firms' ability to raise capital. Third, I discuss the electrification decision of late-entrants.

4 Electrification and Factory Productivity

In this section, I test whether electrification increased factory productivity. First, I compare electrified cotton mills to non-electrified mills to test whether there are differences in factory productivity.[17] On average, electrified cotton mills were 13% more labor-productive and 12% more total factor productive than their non-electrified counterparts.[18]

This comparison demonstrates large differences in productivity between electrified and

[17] TFP is measured as the residual from a Cobb-Douglass production function of output on employment, number of spindles (a measure of physical capital), and number of horsepower. This method was suggested by Gregg (2020). Because this method may suffer from simultaneity and selection biases, I discuss alternative approaches to production function estimation in Appendix C.2.

[18] Appendix Figure A.3 presents the distribution of labor productivity and TFP for electrified factories compared to non-electrified. In each case, the distribution is shifted to the right for electrified factories.

non-electrified factories. However, these differences could reflect selection into electricity adoption rather than a causal effect of electrification. Electrification was costly because manufacturers had to purchase electrical equipment and install transmission wires in the factory. If firms with skilled managers were more productive and more likely to electrify, the estimates above may overstate the productivity gains from electrification. Because I have a panel of establishments, I can control for establishment fixed-effects to capture pre-existing productivity differentials that could be driving the results. I estimate

$$y_{it} = \alpha + \beta Electric_{it} + \gamma_i + \gamma_t + \epsilon_{it}$$

where y_{it} is a measure of productivity, and $Electric_{it}$ is equal to one if factory i is electrified in year t while γ_i and γ_t are fixed effects for the establishment and report year, respectively. Table 1 presents the effect of electrification on output, labor productivity, and TFP. Electrifying factories increased their labor productivity by 10% and TFP by 9% relative to factories that did not electrify. These results show that electrification had a large positive effect on factory productivity but do not explain how factories changed to take advantage of electrification. Next, I test several possible mechanisms by which electrification might have increased productivity.

4.1 Why did electrification increase productivity?

To understand how electrification caused productivity increases, I first test whether electrification caused factories to use a different combination of inputs. One possibility is that electricity simply lowered the costs of energy, encouraging manufacturers to increase their use of power. In Table 2 Column 1, I show that electrification significantly increased the amount of horsepower per worker.[19] Column 2 shows that electrification increased

[19]The differences in horsepower between electrified and non-electrified factories may overstate the true difference in power used. As noted by Du Boff (1967), manufacturers used a larger share of the available horsepower from steam engines than from electric motors, so the relationship between available

the ratio of spindles to employees. Column 3, however, shows that electrifying factories did not significantly increase the number of employees at the plant. Column 4 shows that electricity did not have a significant effect on the capital-output ratio, though the coefficient is consistent with the capital-saving benefits of electrification suggested by David and Wright (2006).

in contrast to the aggregate effects found by David and Wright (2006), though the financial measure of capital invested may not capture the capital-saving electricity benefits they suggested. These differences show that electrified factories were able to restructure their factories to use more energy and capital per worker.

Goldin and Katz (1998) argued that electrification was complementary to skill. Because this data does not include direct measures of skill, I use the age- and gender-composition of the labor force as a proxy for skill.[20] Columns 5 and 6 of Table 2 show the relationship between electrification and the share of employees who were men or children.[21] These results do not show a consistent relationship between electrification and the labor-force composition. However, the gender breakdown may be a weak proxy for skill in this context. The textile industry was one in which women made up a particularly large share of the workforce, and the importance of child labor was declining over the period. As shown in Section 5.1, wages varied substantially within a plant for workers of the same gender, suggesting that gender was an imperfect proxy for worker skill. The wage evidence shown later suggests that there may have been skill-upgrading within age and gender categories.

Another proposed benefit of electrification is that it made it easier to operate a subset of the factory's machines, rather than run all machines jointly. By allowing factories to

horsepower and power used likely differs between electrified and non-electrified factories.

[20] However, as noted by David and Wright (1999), education was only weakly related to the skills most valued by manufacturers.

[21] Children refers to those under the age of 16. There were few regulations on child labor in this period. The state prohibited workers under 12 in 1903, under 13 in 1907, under 14 in 1919, and under 16 in 1937 (Davidson 1939, p.275-278).

efficiently operate some machines while leaving others idle, factories could more easily maintain and adjust machines without interrupting others or run multiple shifts in which not all machines were used simultaneously. Although the reports do not measure time lost to repairs, I use whether the factory ran a night shift as a measure of the scheduling flexibility. Column 7 of Table 2 shows that electrification did not increase the probability of a manufacturer running a night shift.[22] However, plants may have benefited from scheduling flexibility in other ways that are not captured here.

Another possibility is that electrification allowed textile producers to increase the quality of goods they were producing because electricity allowed more precise control of machines than steam or water. Previous researchers have used the yarn count as a measure of textile quality (Wright 1981), but while these reports include descriptions of each plant's output, they do not do so in a way that allows me to index the products' quality in a consistent way.[23] As a proxy for product quality, I use the ratio of the plant's value of output to the pounds of cotton consumed. Manufacturers with a higher ratio were producing more valuable products from a given volume of cotton. Column 8 shows that electrification did not have a significant effect on the quality of output. In Appendix A.4, I discuss alternative measures of product quality. I do not find that electrification increased the likelihood of a factory producing a high-quality output or of changing their product mix from the previous year.

These results show that factory electrification involved changes in the production process as factories adopted more energy- and capital-intensive patterns of production. However, most of the productivity gains from electrification were not just from adding additional capital and energy. Returning to Table 1, the effect of electrification on TFP is almost as large as the effect on labor productivity. The results here point to the

[22]Night work may be a weak proxy for scheduling flexibility. Shiells and Wright (1983) argues that night work was the result of surplus labor and sticky wages.

[23]Examples of product descriptions from the first page of the 1924 report include "Fine gingham and dress goods", "Duck, stripes, and chambrays", "Table damask and yarns", and "Blue denims".

importance of factory reorganization for increasing productivity. By eliminating the belts and shafts, manufacturers could add more machines. However, because the increase in the ratio of spindles to workers does not explain much of the increase in labor productivity, manufacturers must have been able to rearrange the machines in a way to achieve more efficient throughput.[24]

4.2 Partial Electrification

Manufacturers could electrify either by adding electrical equipment to their existing infrastructure or by reconfiguring the entire factory. While I do not observe how exactly manufacturers used electricity, I do observe whether they used electricity as a sole power source or in combination with water or steam.[25] To provide suggestive evidence on the importance of full electrification, I compare the productivity of fully-electrified factories to those only partially electrified. I estimate

$$\log(VO/L)_{it} = \alpha + \beta_1 AllElec_{it} + \beta_2 PartElec_{it} + \gamma_t + \epsilon_{it}$$

where $AllElec_{it}$ is equal to one for fully-electrified factories, $PartElec_{it}$ is equal to one for partially-electrified factories,γ_t is a year fixed-effect, and the omitted category is non-electrified factories.

As shown in Table 3, I find that β_1 is much larger than β_2, suggesting that full electrification provided productivity benefits beyond partial electrification. These results support claims by David and Wright (2006) that existing steam and water infrastructure limited the gains from adopting electricity.

[24] In this section, I have focused on productivity in the textile sector for convenience and clarity. In Section 5.2 I show that electricity increased labor productivity in other industries as well.

[25] 71% of electrified factories used electricity as a sole power source.

5 Electrification and Workers

The above section has shown that electrification provided productivity gains to manufacturers. Here, I discuss the implications of factory electrification for the plant's employees. Adoption of a new technology could benefit workers by making them more productive and increasing their wages. Alternatively, a new technology could replace workers by automating tasks that were previously performed manually.

The results above provide some evidence of the implications for workers. Electrification increased the number of spindles per worker. While this is consistent with an increase in work-intensity,[26] it is also consistent with electricity substituting for non-production tasks by reducing the need to backtrack and making it possible to move materials continuously through the factories. Wages are an important component to pin down the implications of electrification for the plant's employees. Here, I test how electrification affected the distribution of wages within the plant as well as across plants.

5.1 Electrification and the Return to Skill

First, I ask whether electrification increased the wage-dispersion within factories. Cotton mills were asked for the highest and lowest daily wages paid to men and women, but not for information on the total wage bill. Here, I estimate

$$w_{it} = \alpha + \beta Electric_{it} + \gamma_i + \gamma_t + \epsilon_{it}$$

where w_{it} is the wage for each category of high and low/male and female. As shown in Table 4, electrification increased the wages paid to the highest-paid men by about 4.5% and to the highest-paid women by about 3.5%, but did not change the wages paid to the

[26] Textile workers did complain about the "stretch-out" in the 1920s in which they were pushed to operate a greater number of machines (Hall et al. 1987).

lowest-paid members of either group.[27]

The effects of electrification on workers differed on whether electrification complemented or substituted for the tasks they performed.[28] These results suggest that electrification complemented the tasks performed by the best-paid workers, but not by the lowest-paid. Without occupational data, it is difficult to know exactly which tasks were affected, but these patterns are consistent with electricity substituting for low-skilled workers by reducing the need for materials handling by rearranging the factory. The fact that the same pattern is present for men and women indicates that the effects of electrification on workers were broader than simply hiring a small group of skilled male machine operatives.

5.2 Electrification and Average Wages (Pooled OLS)

Here, I turn to the data for factories in other industries. While the textile reports included detailed information to evaluate productivity, the reports included limited information on wages, listing only the high and low daily wages paid to men and women. Factories for other industries, however, reported the total wage bill.

First, I test whether electrification was related to average wages, computed as the total wage bill for the year divided by the number of employees. I estimate

$$w_{it} = \alpha + \beta Electric_{it} + \gamma_{ind} + \gamma_t + \epsilon_{it}$$

where w_{it} is the plant's average wage, $Electric_{it}$ is equal to one if a plant is using electricity

[27]One concern is that firms may have differed in which employees were included when reporting these wages as it is not clear whether they included all employees or only production workers. For example, electrified plants might include the wages of a highly-paid electrician. In 1916, for example, the average daily wage of an electrical worker was reported as $3.00, while the average high male wage at electrified mills was $3.24 and the average high male wage at non-electrified mills was $2.86. However, the fact that the pattern is the same for both men and women suggests that this reflects a change in the return to skill, rather than simply factories hiring a well-paid electrician.

[28]See Acemoglu and Autor (2011) for a discussion of task-based approaches to technological change.

and zero otherwise, and γ_{ind} and γ_t are industry and year fixed-effects respectively. The results in Column 1 of Table 5 show that electrified plants paid considerably higher wages than other plants. On average, electrified factories paid their employees about 16% more than non-electrified factories.

While electrified factories paid higher average wages than non-electrified, the gains from electrification may not have been evenly shared with workers if increased productivity outpaced wages. As shown in Column 2 of Table 5, electrified factories produced over 30% more output per worker than non-electrified factories. To test how much the gains from electrification were shared with workers, I estimate

$$LaborShare_{it} = \alpha + \beta Electric_{it} + \gamma_{ind} + \gamma_t + \epsilon_{it}$$

where $LaborShare_{it}$ is the labor share, calculated as the wage bill divided by the value of output, $Electric_{it}$ is equal to one if a plant is using electricity and zero otherwise, and γ_{ind} and γ_t are industry and year fixed-effects respectively. The results in Column 3 of Table 5 show that electrified factories on average paid about a 4% lower share of their output to workers. Although average wages increased, output per worker increased even more. The reduction in the labor share is consistent with the increased investment in capital involved in electrification.[29]

5.3 Selection on Observables

The section above has shown that electrified factories were more productive and paid higher wages, but these differences may reflect selection into electrification. If, for example, factories with better management selected into electrification, the coefficients above may overstate the effects of electrification. Ideally, an instrumental variable strategy could be used to address endogeneity concerns, but there does not seem to be a valid instrument

[29] Appendix Tables A.12-A.14 show that these results are robust to alternative estimation approaches.

for electrification in this period (Gray 2013). In Appendix Section D, I discuss possible IV strategies, but exclude these results from the main analysis due to concerns about the instruments.

Here, I focus on selection on observables, introducing factory-level controls that might have explained the high wages and productivity of electrified factories. Atack et al. (2008) and Goldin and Katz (1998) use a similar approach to identify the effect of steam and electricity adoption respectively. I include controls for the capital-labor ratio, energy-labor ratio, factory size, and share of women employees. The results, presented in Table 6 support the results above and suggest that observable characteristics do not explain the higher wages and productivity of electrified factories.

5.4 Linked Factories

Linking factories in the other industries dataset through time is challenging as factory names do not always identify factories precisely across years. For example, some plants are listed under the name of an owner in one year and not in others.[30] I have been able to link 1,140 plants between the reports for 1915 and 1920. In this panel, 24% of plants had electrified in 1915 while 36% had electrified by 1920. Using this panel, I can control for plant-specific unobservables that might drive both electrification and wages. Here, I estimate

$$y_{it} = \alpha + \beta Electric_{it} + \gamma_i + \gamma_t + \epsilon_{it}$$

for average wages, labor productivity, and labor share, controlling for time and plant fixed-effects. The results, presented in Table 7, are in the same direction as the OLS and IV results, though smaller and the coefficient on $Electric_{it}$ is no longer significant for the labor share. The smaller effect of electrification on established plants reflects

[30]See Appendix A.2 for a discussion of the difficulties in linking plants in these reports.

the fact that within-plant variation shuts down important channels of adjustment. While established manufacturers benefitted from replacing steam or water with electricity, taking advantage of the full set of benefits of electrification required substantial factory redesign or the construction of a new factory (David and Wright 1999, p. 23-28). The differences between the effect of electrification in the linked sample and the repeated cross-section further support the claim that the productivity gains from electrification were the result of factory reorganization.[31]

6 Electricity Adoption

Because manufacturers could realize large productivity gains from electricity, why didn't all firms electrify? The costs of electrification must have been prohibitive. While the data to quantify how these costs differed across factories is not available, in this section I provide suggestive evidence that capital constraints and a lack of access to purchased electricity limited factories' ability to electrify.

6.1 Electrification and Access to Hydropower

A manufacturer wanting to electrify had two options: they could generate their own power or purchase from an electric utility. In Appendix Figure A.4, I show the location of hydropower sites in North Carolina and adjacent states in 1915 and 1926. In Figure 3, I present the coefficients β_d from

$$Electric_{it} = \alpha + \sum_{d=10}^{70} \beta_d \mathbb{1}_{Distance \in (d-10,d]} + \gamma_t + \gamma_{industry} + \epsilon_{it}$$

[31]Factories could reorganize machines even within an already-constructed factory. Devine (1983) provides the example of the U.S. Government Printing Office which was able to add 40 printing presses to the same building after electrifying.

where $Electric_{it}$ is equal to one if the factory is electrified, $\mathbb{1}_{Distance \in (d-10,d]}$ is equal to one if the factory is between $d - 10$ and d kilometers away from a hydropower plant operating in that year, and γ_t and $\gamma_{industry}$ are year and industry fixed-effects. Factories within 30 km of a hydropower plant are more likely to be electrified than factories more than 70 km away, but factories between 30 and 70 km were no more likely to electrify.

These results suggest the role of the electric grid in making widespread electrification possible. Hydropower sites were limited by geography, but improvements in electricity transmission made it possible to transmit electricity at greater distances. While year-by-year maps of the electric grid have not survived for this period, I show the map of hydropower plants and transmission lines existing in 1912 in Appendix Table A.7. Large parts of the state were located far from the transmission network. Manufacturers in these areas could not have purchased electricity from a utility company, even if they wanted to, and would have had to generate their own power.

6.2 Electrification and Organizational Form

Because electricity adoption was costly, firms with better access to capital may have been more able to electrify. One year of the other industry reports includes information on the organizational form of factories. Each factory is listed as owned by either a corporation, partnership, or an individual. In Table 8, I show that factories owned by corporations were much more likely to use electricity than factories owned by individuals or partnerships. However, Column 3 shows that the relationship between incorporation and electrification primarily reflects differences in the amount of capital invested. Because incorporation is endogenous, firms with a greater need for capital may have selected into incorporation. This pattern is consistent with the results in Gregg (2020) that incorporation helped firms finance productivity-enhancing investments. Carlton and Coclanis (1989) emphasized the financial underdevelopment of the postbellum South. These capital constraints likely prevented manufacturers from making the investments needed to electrify.

6.3 Factory Characteristics and Electrification Timing

Lacking establishment-level data, most discussions of electricity diffusion have focused on industry-specific causes. However, it is difficult to separate the causes of electrification from other features of the industry. Goldfarb (2005), for example, linked electrification to industry-specific innovations which made electrification feasible. By restricting to within-industry variation in the timing of electrification, I can isolate factory-specific features that contributed to electrification.

Using the panel of cotton mills, I test how characteristics of non-electrified mills related to their probability of electrifying in the next period. The results, presented in Table 9, illustrate the factory characteristics related to adoption. Three distinct patterns stand out. First, steam-powered factories were more likely to electrify than those using water. Because waterpower had a low marginal cost, energy cost savings from electrification would have been more important for steam-powered factories. Second, larger mills were more likely to electrify. Because electrification required a fixed cost, larger plants may have been able to spread the cost of electrifying over more units of output.[32] Third, the timing of electrification was not related to a factory's initial productivity.

6.4 Energy Choices of New Entrants

While established factories may have been "locked-in" to an old technology, new factories should have found it easier to adopt the newest technology and electrify. New mills could also take advantage of the full benefits of electrification in the design of their factories. Using the panel of cotton mills, I can document changes in the power sources chosen by new entrants. Figure A.5 displays the power sources chosen by new mills by year. Because

[32] This finding also rules out alternative theories that smaller factories were more likely to electrify because steam engines were not economical at small scales (DuBoff 1967).

different numbers of mills enter each year, Figure A.6 plots the power sources chosen by new mills over each five year period. Electricity became the dominant technology for new mills before it did for cotton mills in general. After 1915, mills overwhelmingly entered using electricity. This pattern suggests that established factories were locked into steam or water and these sunk investments slowed the spread of electrification.

However, some late entrants did not immediately adopt electricity. Of the 136 mills that entered after 1919, nineteen did not use electricity. The decisions of these mills also suggest reasons a factory might choose not to electrify. Of these, three did not construct a new factory, but rather purchased an established factory. The capital invested in an old technology did not immediately depreciate when electrification became feasible. Five of the non-electrified entrants were in towns where no other electrified mills were located, pointing to the importance of the electric grid. One new entrant was a second establishment owned by the same firm as a older steam-powered mill. Mills who entered after 1919 overwhelmingly chose to electrify when possible.

These differences in power use between new and older mills suggest that the late growth of the textile sector in North Carolina and other southern states may have allowed these factories to adopt electricity more easily than the more established textile sector in New England. In 1929, for example, 77% of power in North Carolina cotton mills came from purchased electricity, though that number was only 41% in Massachusetts (United States Department of Commerce 1933b, pp. 233 and 388). This combination of large productivity gains and technological lock-in created the potential for regional leap-frogging.

7 Conclusion

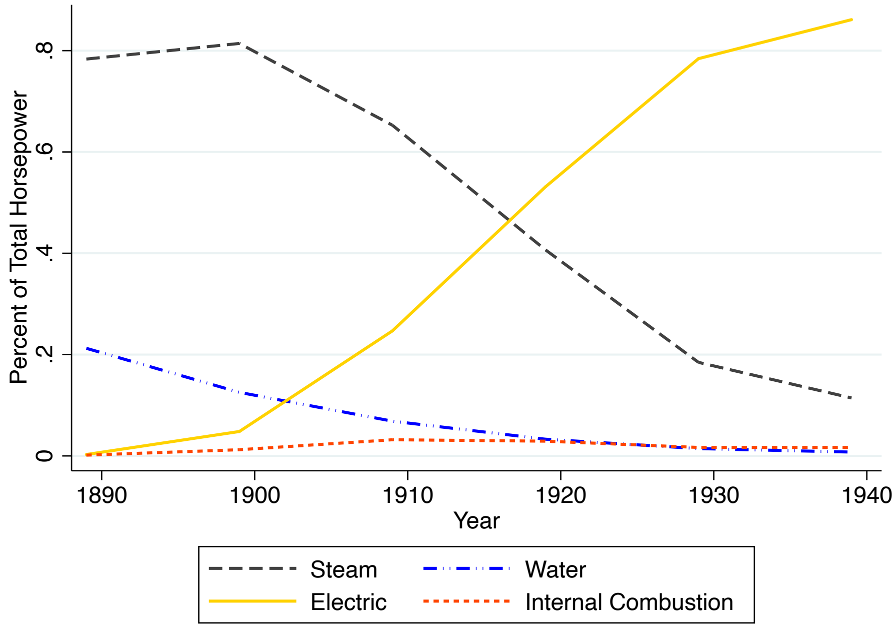
Electricity was one of the major technological innovations of the twentieth century. However, the macroeconomic effects of electrification arrived slowly. Although factories first began to adopt electricity in the 1880s, steam and water remained important sources of manufacturing power for more than fifty years. The productivity results in my paper make this lag even more puzzling. Manufacturers who adopted electricity saw large productivity increases - why didn't every manufacturer adopt electricity?

I provide evidence that the costs of adoption mattered. Factories near hydropower plants were more likely to electrify, indicating the importance of purchased electricity, and incorporated factories were more likely to electrify, suggesting the role of capital constraints. While electrification was a decision made at the firm level, external factors, such as capital markets and the electrical grid, were important for allowing electricity to be widely adopted.

Taken together, these results help explain why electricity was such a revolutionary technology and why it took so long for electricity to achieve its most dramatic effects. Electricity allowed manufacturers to adopt more productive production processes. However, widespread electrification required the development of complementary technologies, such as long-distance transmission, and financial institutions that made it possible for manufacturers to invest in electrification. Established manufacturers had already invested in old technologies, and these investments prevented them from taking full advantage of electricity. As these constraints were lifted, more manufacturers electrified, contributing to the dramatic economic growth of the early twentieth century.

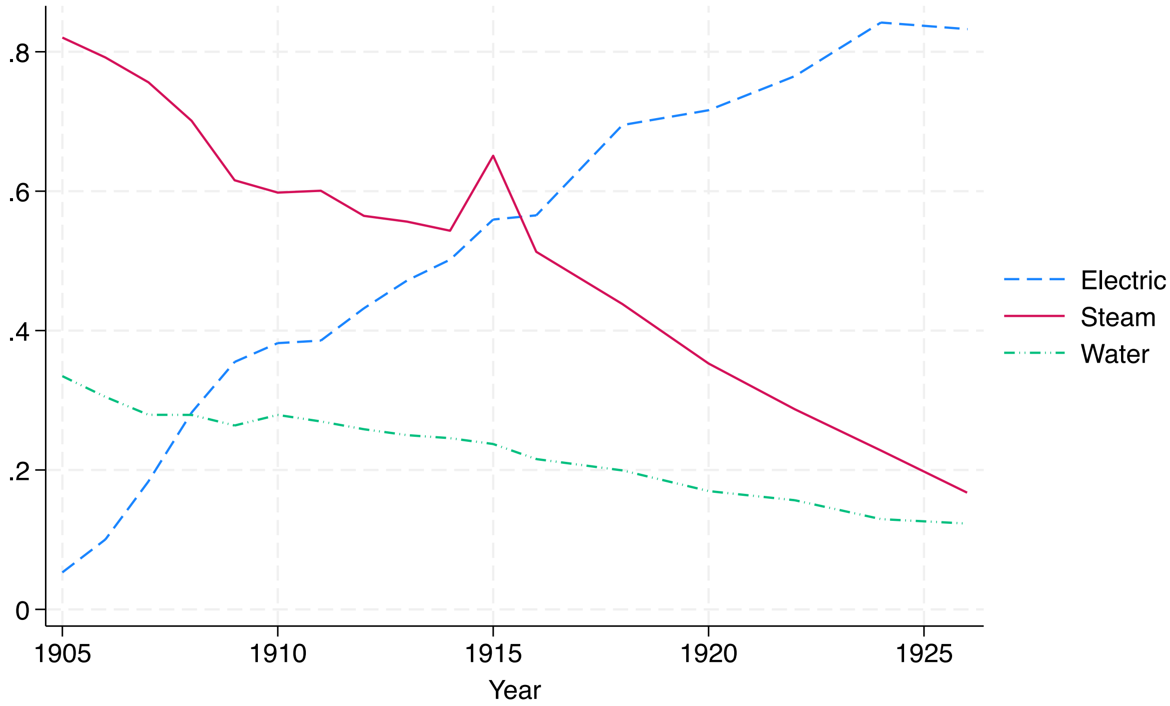
Figures and Tables

Figure 1: Share of Energy used in Manufacturing by Type (US)



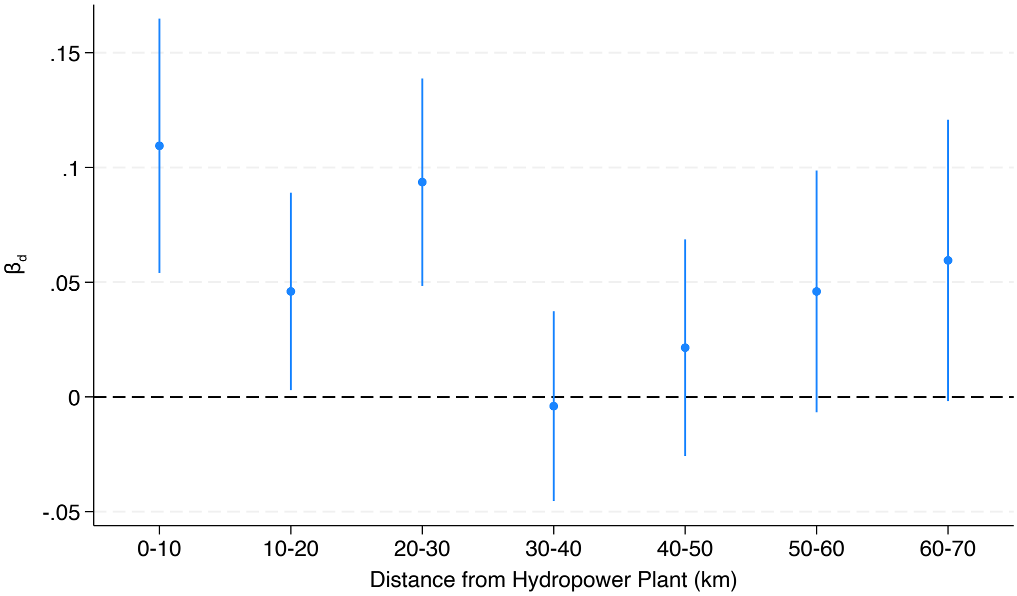
Source: Devine (1983) Table 3, from Census of Manufacturing.
Notes: This graph presents the share of horsepower used in US manufacturing provided by each type of power.

Figure 2: Power Sources: North Carolina Cotton Mills



Source: North Carolina Department of Labor Reports
Notes: This graph presents the share of factories using each type of power. Because some factories use multiple sources, the shares sum to greater than one.

Figure 3: Hydropower Plant Location and Probability of Electrification



Notes: This plots the coefficients β_d from

$$Electric_{it} = \alpha + \sum_{d=10}^{70} \beta_d \mathbb{1}_{Distance \in (d-10,d]} + \gamma_t + \gamma_{industry} + \epsilon_{it}$$

The factories are from the other industries sample for 1915-1926, and the hydropower sites are taken from Hay (1991). The coefficients include 95% confidence intervals and are clustered at the county-year level.

Table 1: Electrification Increased Productivity (Textiles)

	(1) log(VO)	(2) log(VO/L)	(3) TFP
Electric	0.128***	0.103***	0.0859**
	(3.02)	(2.76)	(2.26)
Observations	2633	2614	2356
Year FE	YES	YES	YES
Establishment FE	YES	YES	YES
Sample	Textiles	Textiles	Textiles
Years	1912-1926	1912-1926	1912-1926

t statistics in parentheses

Standard errors clustered at establishment-level. VO denotes value of output, L denotes number of employees. TFP is the residual of log(VO) on log(L), log(spindles), and log(horsepower). Electric equals 1 if the factory is electrified.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 2: Electrified Factories Increased Capital- and Energy-Intensity (Textiles)

	(1) log(HP/L)	(2) log(S/L)	(3) log(L)	(4) log(K/VO)	(5) Men/L	(6) Children/L	(7) Night Shift	(8) log(VO/pounds)
Electric	0.119***	0.0659**	0.0158	-0.0727	-0.00598	0.00142	0.0236	0.0656
	(4.36)	(2.58)	(0.63)	(-1.17)	(-0.78)	(0.18)	(0.95)	(1.26)
Observations	4608	4787	4965	2433	2724	2698	4956	2498
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Establishment FE	YES	YES	YES	YES	YES	YES	YES	YES
Sample	Textiles	Textiles	Textiles	Textiles	Textiles	Textiles	Textiles	Textiles
Years	1905-1926	1905-1926	1905-1926	1912-1926	1912-1926	1912-1926	1905-1926	1912-1926

t statistics in parentheses

Standard errors clustered at establishment-level. HP denotes horsepower, S denotes number of spindles, L denotes of workers, VO denotes value of output, pounds denotes pounds of cotton used, K denotes capital invested. Night Shift is equal to one if the mill ran a night shift and zero otherwise. Electricity is equal to one if the factory used electricity.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Partial Electrification and Productivity (Textiles)

	(1)	(2)	(3)
	log(VO)	log(VO/L)	TFP
All Electric	0.340***	0.105***	0.107***
	(4.74)	(3.10)	(3.18)
Partially Electrified	0.642***	0.0128	0.0325
	(7.72)	(0.39)	(1.04)
Observations	2633	2614	2356
Year FE	YES	YES	YES
Sample	Textiles	Textiles	Textiles
Years	1905-1926	1905-1926	1905-1926

t statistics in parentheses

Standard errors clustered at establishment level. VO denotes value of output, L denotes number of employees. TFP is the residual of log(VO) on log(L), log(spindles), and log(horsepower). All Electric is equal to one if the factory uses electricity as a sole power source and Partially Electrified is equal to one if the factory uses electricity in combination with water or steam. The omitted category is factories not using electricity.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 4: Electrification Increased Wages for Best-Paid Workers (Textiles)

	(1)	(2)	(3)	(4)
	log(High - Men)	log(High - Women)	log(Low - Men)	log(Low - Women)
Electric	0.0454**	0.0312**	0.00677	-0.0129
	(2.22)	(2.44)	(0.42)	(-0.78)
Observations	4245	4196	4224	4166
Year FE	YES	YES	YES	YES
Establishment FE	YES	YES	YES	YES
Sample	Textiles	Textiles	Textiles	Textiles
Year	1905-1926	1905-1926	1905-1926	1905-1926

t statistics in parentheses

Standard errors clustered at establishment-level. High/Low denotes the top/bottom daily wages paid to workers of each gender. Electric is equal to one if the factory used electricity.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Electrification and Wages (Other Industries)

	(1) log(Avg. Wage)	(2) log(VO/L)	(3) Labor Share
Electric	0.389***	0.545***	-0.0370***
	(20.54)	(16.83)	(-6.97)
Observations	12242	12176	12023
Year-Industry FE	YES	YES	YES
Sample	Other Industries	Other Industries	Other Industries
Years	1915-1926	1915-1926	1915-1926

t statistics in parentheses

Standard errors clustered at the county-year level. Avg. Wage is the total wage bill divided by the number of workers, VO/L is the value of output divided by the number of workers, and laborshare is the wage bill divided by the value of output. Electric is equal to one if the factory used electricity.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Electrification and Wages (Other Industries - Controls)

	(1)	(2)	(3)
	log(VO/L)	log(Avg. Wage)	Labor Share
Electric	0.392***	0.262***	-0.0245***
	(12.42)	(13.03)	(-3.70)
log(K/L)	0.502***	0.309***	-0.0543***
	(42.41)	(28.04)	(-20.67)
log(L)	0.0762***	0.123***	0.0185***
	(7.52)	(11.61)	(6.87)
log(hp/L)	0.0410***	-0.0432***	-0.00753**
	(3.54)	(-3.87)	(-2.46)
% Women	-0.0626	-0.481***	-0.0871***
	(-0.64)	(-5.23)	(-3.93)
Observations	8318	8361	8097
Year-Industry FE	YES	YES	YES
Sample	Other Industries	Other Industries	Other Industries
Years	1915-1926	1915-1926	1915-1926

t statistics in parentheses
Standard errors clustered at the county-year level. Avg. Wage is the total wage bill divided by the number of workers, VO/L is the value of output divided by the number of workers, and Labor Share is the wage bill divided by the value of output. Electric is equal to one if the factory used electricity.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Electrification and Wages (Other Industries - Linked)

	(1)	(2)	(3)
	log(VO/L)	log(Avg Wage)	Labor Share
Electric	0.220***	0.154**	-0.0166
	(2.69)	(2.31)	(-0.96)
Observations	2135	2131	2131
Year FE	YES	YES	YES
Establishment FE	YES	YES	YES
Sample	Other Industries	Other Industries	Other Industries
Years	1915-1926	1915-1926	1915-1926

t statistics in parentheses

Standard errors clustered at establishment-level. VO/L is the value of output divided by the number of workers. Avg. Wage is the total wage bill divided by the number of workers. Labor Share is the total wage bill divided by the value of output.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 8: Factories Owned by Corporations Were More Likely to Use Electricity

	(1) Electric	(2) Electric	(3) Electric
Corporation	0.261***	0.0877***	0.0328*
	(15.80)	(5.78)	(1.88)
Partnership	0.00388	0.00555	0.00471
	(0.24)	(0.41)	(0.35)
log(Capital Invested)			0.0302***
			(6.67)
Observations	3332	3332	3300
Industry FE	N	Y	Y
Sample	Other Industries	Other Industries	Other Industries
Year	1915	1915	1915

t statistics in parentheses

Omitted category is individual proprietorships. Electric is equal to one if the factory used electricity.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 9: Timing to Electrification (Textiles)

	(1) Adopt Next Period	(2) Adopt Next Period	(3) Adopt Next Period	(4) Adopt Next Period	(5) Adopt Next Period
Steam Only	0.0831***				0.105***
	(4.86)				(3.01)
Water and Steam	0.0414**				0.0765*
	(2.27)				(1.86)
log(hp)		0.0369***			-0.00990
		(3.96)			(-0.27)
log(L)			0.0430***		0.0728**
			(5.03)		(2.22)
log(VO/L)				-0.0116	0.00791
				(-0.39)	(0.25)
Observations	2313	2191	2210	745	718
Sample	Textiles	Textiles	Textiles	Textiles	Textiles
Years	1905-1926	1905-1926	1905-1926	1912-1926	1912-1926

t statistics in parentheses

Omitted category is all-water powered plants. hp denotes horsepower, L denotes labor, VO denotes value of output. Adopt Next Period is equal to one if the mill adopted electricity in the next period. Standard errors clustered at the factory level.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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