Connecting to Electricity: Technical Change and Regional Development *

Atsuki Kotani
The University of Tokyo

This version: November 12, 2024

Abstract

The technical change from steam engines to electric motors dramatically transformed manufacturing activities during the Second Industrial Revolution. This paper explores how this technical change progressed and what consequences it brought for the evolution of economic geography. I hypothesize that electric motors powered by purchased electricity lowered barriers to entry in the manufacturing sector due to their significantly lower fixed costs compared to steam engines. To examine this hypothesis, I exploit the historical expansion of electricity grids in early 20th-century Japan and newly digitized establishment-level official records, including information on power sources of establishments. Descriptive evidence shows that electric motors were widely adopted by establishments of all sizes, whereas steam engines were primarily adopted by large establishments, indicating lower fixed costs of electric motors. Using hydropower potential as an instrument, I document that new entrants played a crucial role in driving this technical change and stimulating manufacturing activities. Overall, these findings lend substantial support for the hypothesis. Furthermore, I find that geographical variation in the timing of electricity access influenced subsequent population growth, indicating a persistent impact of this technological shock.

JEL Classification: F63, L26, L94, N65, O14, R12
Keywords: Technical change, Entrant, Structural transformation, Historical persistence

*I am grateful to my advisers Yasuyuki Sawada, Kensuke Teshima, and Tetsuji Okazaki for invaluable guidance on this project. I also thank Johannes Boehm, Clément Gorin, Jun Goto, Hidehiko Ichimura, Hiro Ishise, Jingcheng Jiang, Hiroyuki Kasahara, Daiji Kawaguchi, Wolfgang Keller, Shinnosuke Kikuchi, Motohiro Kumagai, Yoshito Takasaki, Junichi Yamasaki, and Hyunjoo Yang as well as numerous seminar participants at the University of Tokyo, Doshisya University, Kyoto Summer Workshop on Applied Economics 2024, Sogang University, The 19th Applied Econometrics Conference, and ISER Osaka University for their helpful comments and suggestions. I thank Ryosuke Arai, Yutaka Arimoto, So Kazama, Kentaro Nakajima, Tetsuji Okazaki, and Yasushi Toyoda for kindly sharing data. This research was also supported by CARF, the University of Tokyo. Financial support from the International Leading Research (Nos.22K21341) is gratefully acknowledged. This paper was awarded the 19th Applied Econometrics Conference and the 2024 Moriguchi Prize by the Institute of Social and Economic Research, Osaka University. Atsuki Kotani: Department of Economics, The University of Tokyo. (Email: kotani-atsuki@g.ecc.u-tokyo.ac.jp)

1 Introduction

Technical change is a key driver of economic growth, and the early 20th century witnessed a groundbreaking shift in general-purpose technology—from steam engines to electric motors (Bresnahan and Trajtenberg, 1995). The process of electrification entailed an expansion of manufacturing activities, leading to structural transformation and socioeconomic change (Mumford, 1934; Gordon, 2017). While it is well documented that many technologies, such as the steam engine, are slow to diffuse despite their considerable benefits (Hall and Khan, 2003; Hall, 2004), the transition from steam engines to electric motors occurred rapidly.[1] Despite its substantial and swift impact on economic activities, we know little about how this technical change progressed and what consequences it brought about for long-run regional development.

The primary goal of this paper is to examine the mechanism that underlies this dramatic transition from steam engines to electric motors that accompanied the rapid expansions of manufacturing activities, highlighting the driving forces behind the structural change during the Second Industrial Revolution. Specifically, I shed light on the substantial reduction in *fixed costs* of technology adoption that accompanied the shift from steam engines to electric motors driven by purchased electricity. While both steam engines and electric motors are considered general-purpose technologies designed to convert energy into rotary motion for manufacturing, they differ significantly in their adoption costs. This technical distinction leads to the hypothesis that electric motors, with their much lower fixed costs compared to steam engines, played a crucial role in lowering barriers to entry in the manufacturing sector with powered factory, in turn stimulating manufacturing activities.

In this paper, I investigate this hypothesis by exploiting the historical expansion of electricity grids in early 20th-century Japan and newly digitized official records. Due to topographical features in Japan—characterized by mountainous terrain and fast-flowing rivers—and transmission technology development, the expansion of electricity grids during this period was largely driven by hydropower generation. This historical context makes it possible to isolate the variation in grid expansion that is attributable to geographic suitability for hydropower generation, which I use as an instrument for early electricity access. Additionally, to explore the underlying mechanisms of this technical change and its impact on manufacturing activities, I collect and digitize establishment-level official records, including information on power sources and employees, as well as municipality-level data on electricity access. This historical context and newly digitized data allow for identifying the effects of electricity access on manufacturing activities, with a particular focus on the role of electric motors and new entrants.

[1] For example, in 1910, approximately 75% of horsepower in Japan was generated by steam engines, but by 1930, electric motors had overtaken steam engines, accounting for 80% of horsepower (Minami, 1979).

I begin by describing the historical background. Although the steam engine was an iconic innovation of the First Industrial Revolution, its high fixed costs—requiring extensive and complex workshops—hindered its widespread adoption. In contrast, electric motors powered by purchased electricity involved much lower fixed costs, as they freed manufacturers from the need to install on-site power generators and allowed for simpler, more compact operations. Using establishment-level data, I demonstrate that smaller establishments were less likely to adopt steam engines. Furthermore, I find that after the electricity grid expansion, there was a significant and uniform increase in the adoption of electric motors across all establishment sizes. These findings suggest that, while steam engines favored larger factories, electric motors democratized power-driven production and lowered barriers to entry in the manufacturing sector.

To test the hypothesis motivated by the historical context, I introduce hydropower potential as an instrument for early electricity access. This measure, developed in the hydraulic engineering literature, evaluates the geographical potential for hydroelectric power generation (Basso and Botter, 2012; Müller et al., 2014). Specifically, I employ the potential for run-of-river hydropower generation estimated by Arai et al. (2022), calculated as the product of water volume and hydraulic head height. I use this geographical variation as an instrument, controlling for streamflow and ruggedness that can otherwise influence local economic activities.[2]. To support the validity of the instrument, I provide two sets of evidence. First, higher hydropower potential leads to the construction of hydropower stations and early electricity access, confirming the instrument's relevance. Second, hydropower potential is correlated with manufacturing activities only after the expansion of electricity grids. This result indicates that hydropower potential offers a plausible source of variation in electricity access that is exogenous to preexisting determinants of manufacturing activities.

As a baseline analysis, I estimate the effect of electricity access on manufacturing activities using hydropower potential as an instrument. The results show that electricity access significantly increased the number of establishments, resulting in approximately 6.6 times the average increase. Moreover, electricity access not only stimulated the adoption of electric motors but also increased manufacturing employment. Overall, these findings suggest that electricity access played a pivotal role in driving manufacturing activities in early 20th-century Japan. A series of robustness checks confirm that these effects were not driven by unobserved preexisting regional characteristics or time-varying confounding factors, such as improvements in railway access or infrastructure investments.

Furthermore, by isolating the effect by new entrants and incumbents, I explore the underlying

[2]Several studies have used hydropower potential as an instrument for the construction of hydroelectric power stations, the length of high-voltage transmission lines, and the amount of electricity used in manufacturing (Leknes and Modalsli, 2020; Gaggl et al., 2021; Reichardt, 2024)

mechanisms of this technological change and its impact on manufacturing activities. The estimation results indicate that the increase in the number of establishments was primarily driven by new entrants. In particular, new entrants accounted for 70% of the total effect on electric motor adoption and 87% of the total effect on the increase in manufacturing employment. These findings suggest that electric motors, with their significantly lower fixed costs compared to steam engines, reduced entry barriers in the manufacturing sector, thereby stimulating manufacturing activities.

In the last part of the analysis, I examine whether electricity access changes the trajectory of regional development in the long run. Using population data from 1908 to 1935, I find that municipalities with early electricity access experienced substantial population growth even during the period of grid expansion in the other areas. The estimation results indicate that gaining electricity access one year earlier led to a 10% increase in population growth between 1908 and 1935. This disparity in regional growth, driven by the timing of electricity access, suggests the possibility of agglomeration forces in manufacturing that may have hindered industrialization in other regions. Furthermore, to explore the persistence of these effects, I examine their impact on today's economic activities using firm-level data. The results show that municipalities with early electricity access continue to enjoy larger economic activities, indicating a lasting advantage even after a century.

Related Literature and Contribution This study brings new insights to the literature on the historical impact of electrification by focusing on the technical change from steam engines to electric motors.[3] Previous work has examined the effects of electricity access or the construction of power stations on various economic outcomes, such as agricultural productivity (Kitchens and Fishback, 2015; Lewis and Severnini, 2020), health conditions (Lewis, 2018; Clay et al., 2024), and labor conflict (Molinder et al., 2021). Notably, using census of population, Leknes and Modalsli (2020) and Gaggl et al. (2021) find that electrification spurred manufacturing activities but decreased the share of agricultural employment, driving structural transformation during the Second Industrial Revolution. While most of the literature examines the effects of electrification broadly, recent work by Reichardt (2024) specifically focuses on the transition from steam engines to electric motors.[4] He associates this transition with a decrease in the average establish-

[3]This paper also relates to the literature evaluating the impacts of electricity access in developing countries today. In contrast to the studies in the historical context during the Second Industrial Revolution, previous research has found mixed evidence. Some research find substantial impacts of electricity access (Dinkelman, 2011; Rud, 2012; Lipscomb et al., 2013; Fried and Lagakos, 2023; Kassem, 2024), whereas others estimate modest welfare gains (Lee et al., 2020; Burgess et al., 2023; Burlig and Preonas, 2024). In relation to my work, Kassem (2024) attributes the positive effects of electricity access in Indonesia to increased firm turnover, highlighting the role of firm dynamics in the benefits of electrification.

[4]As related work, Goldin and Katz (1998) argue that the adoption of electric motors increased the relative demand for skilled workers by enabling a shift to continuous process and batch production methods. Building on this

ment size and a reduction in wealth inequality, utilizing state-by-industry statistics in the U.S. and inheritance tax data in the Netherlands, respectively. Reichardt (2024) provides a theoretical framework highlighting the significant role of electric motors, particularly due to their much lower fixed costs compared to steam engines, in encouraging entrepreneurship and reshaping socioeconomic structures.[5] In contrast to existing studies, this paper contributes to the literature by using establishment-level data and providing the first empirical evidence that the *new entrants* played a crucial role in the technological transition from steam engines to electric motors and in stimulating manufacturing activities. These findings underscore the micro-level mechanisms driving structural transformation and socioeconomic change during the Second Industrial Revolution.

In addition, this paper contributes to our understanding of the evolution of the geography of economic activities. While several studies highlight the significant role of geographical fundamentals in shaping the spatial distribution of economic activities (e.g., Davis and Weinstein, 2002, 2008; Bosker et al., 2013; Bakker et al., 2021), there is also substantial evidence that temporary shocks can result in persistent or even permanent shifts in these spatial patterns (e.g., Redding et al., 2011; Bleakley and Lin, 2012; Kline and Moretti, 2014; Hanlon, 2017). Within this literature, this paper is closely related to studies that investigate the long-run impact of specific technological shocks on the spatial evolution of economic activities, which include studies on plough (Alesina et al., 2013), printing press (Dittmar, 2011), steam engine (Yamasaki, 2023) and tractors (Kitamura, 2022). This paper is distinct from these previous studies in two ways. First, I shed light on the transition from steam engines to electric motors, a technological shift that profoundly affected manufacturing activities of establishments of all sizes. Second, and most importantly, this research empirically investigates the extent to which the spatial difference in the timing of technological change influences the trajectory of regional development. Specifically, the findings from the long-run analysis suggest that the regions that were able to adopt electric motors early on enjoyed a lasting advantage in subsequent development. The finding is consistent with the mechanism that technological shocks in the manufacturing sector accumulate over time, influencing the long-run pattern of regional development (Desmet and Rossi-Hansberg, 2009; Michaels et al., 2012).[6]

argument, Kawaguchi et al. (2024) exploit establishment-level data from the silk-weaving industry in Japan to assess the impact of electrification on skill demand and wage structures.

[5] Reichardt (2024) defines *scale bias* as the degree to which technical change affects the relative productivity of large and small firms. Based on this definition, he demonstrates that the transition from steam engines to electric motors represents a *small-scale-biased* technical change. This is because electric motors, which involve lower fixed costs compared to steam engines, stimulate entrepreneurship and lead to a reduction in the average size of firms.

[6] In this literature, several studies discuss the mechanisms underlying the spatial dynamics of technological leadership (Brezis et al., 1993; Brezis and Krugman, 1997; Rosenberg and Curci, 2023; Hornbeck et al., 2024; Berkes et al., 2024). For example, Brezis et al. (1993) attribute these dynamics to investment accumulation in old technologies, which can make new technologies less attractive. In this context, this paper provides empirical evidence that

Finally, this paper contributes to studies on industrialization in Japan, which saw unprecedented growth in manufacturing activities during the early 20th century. Previous research has explored various drivers of Japan's industrialization, including modern institutions (Sussman and Yafeh, 2000), the modern banking system (Tang and Basco, 2023), international trade liberalization (Bernhofen and Brown, 2004, 2005), government subsidies to firms (Morck and Nakamura, 2018), technological advancements in the cotton spinning industry (Braguinsky et al., 2021), railways (Tang, 2014; Yamasaki, 2023), secondary school (Ichimura et al., 2024), and technology absorption (Juhász et al., 2024). While few studies have specifically assessed the role of electricity access in Japan's industrialization, Minami (1979) describes the transition from steam engines to electric motors, arguing that electric motors, with their simpler layouts, favored the growth of small-scale manufacturing activities. This paper provides empirical support for Minami (1979)'s argument through causal assessment and extends it by examining to what extent electricity access contributed to the rise of manufacturing activities. Moreover, I have successfully harmonized the municipality transitions from 1900 to 2020 by leveraging various data sources, allowing for a detailed spatial analysis of long-term effects.[7] To the best of my knowledge, this is the first study to analyze pre-war Japan at the municipality-by-year level.

The rest of the paper is structured as follows. Section 2 describes the historical context and data. Section 3 discusses the empirical strategy and two sets of evidence that motivate it. In Section 4, I present the short-run effects of electricity access on manufacturing activities. Then, Section 5 shows the long-run effects of early electricity access on population dynamics and today's economic activities. Finally, Section 6 concludes.

2 Historical Background and Data

This section describes the historical background of the expansion of electric grids in early 20th-century Japan and the resulting transition from steam engines to electric motors in the manufacturing sector (Subsection 2.1). It then explains how I constructed the municipality-level dataset that captures electricity supply status and manufacturing activities, along with summary statistics for the dataset (Subsection 2.2).

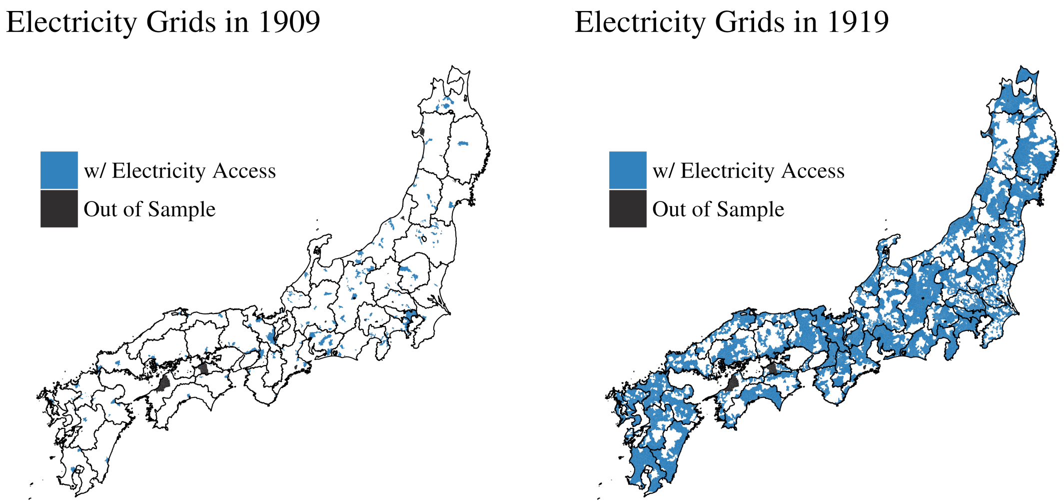
2.1 *Historical Background*

Expansion of Electricity Grids in Japan In 1883, Tokyo Electric Co. (Tokyo Dento), the first electric utility company in Japan, was founded and began supplying electricity in Tokyo. Fol-

the timing of electricity access can alter the spatial pattern of technological leadership through entrants with new technologies.

[7] Since spatial scale can matter when examining the persistence of the effects of shocks (Lin and Rauch, 2022), municipality-level analysis provides a more granular understanding of the long-term effects.

Figure 1: Expansion of Electricity Grids in Japan



Notes: These maps show the municipality-level status of electricity access in 1909 (left) and 1919 (right). "w/ Electricity Access" indicates the municipalities where electricity supply had started by the year, and "Out of Sample" refers to those excluded from the analysis due to missing data, such as electricity access or population information. The black line represents the prefecture boundary.
Source: Ministry of Communications (1910, 1920)

lowing its establishment, several other electric utility companies emerged to supply electricity in metropolitan areas such as Tokyo, Kyoto, and Osaka. These companies were involved in generating, transmitting, and distributing electricity to their customers, primarily catering to the demand for lighting. Initially, they relied on small-scale thermal power plants near their customer bases. The Japanese government implemented a licensing system in 1896 as the electric supply industry gradually expanded. This system required companies seeking to enter the electric utility business to obtain a government-issued license, which delineated their service areas (Research Committee on Electric Utility Policy ed., 1965).

After 1905, there was a significant expansion in electricity supply areas, primarily driven by hydroelectric power generation. Figure 1 displays the municipality-level status of electricity access in 1909 and 1919, illustrating there was a rapid expansion of electricity grids during this period. Kurihara (1964) identifies two main reasons for this rapid expansion: the lower generation costs of hydroelectric stations and transmission technology development. First, hydroelectric stations could produce electricity at a lower cost than thermal power plants. In Osaka and Tokyo, where thermal power was the primary source in 1900, electricity prices were about 1.5 to 3 times higher compared to Kyoto and Fukushima, where hydroelectric power generation predominated. Also, Japan's unique topography—characterized by mountainous terrain and fast-flowing rivers—was well-suited for hydropower generation. Second, while hydropower generation is geographically restricted to mountainous areas, significant improvements in transmission technology during the 1900s made it possible to supply electricity generated by hydropower plants over wider areas.[8] This technological advancement led to a dramatic increase in electricity demand. Figure A1 displays the total amount of electricity generated by hydropower and thermal stations. It shows that electricity generated by hydropower plants began to increase rapidly around 1907, aligning with Kurihara (1964)'s rationale for the grid expansion.

Technical Change: From Steam Engine to Electric Motor The steam engine, a hallmark technology of the Industrial Revolution, was first introduced in Japan in the 1860s with the establishment of a metal-producing factory by the Tokugawa Shogunate. Subsequently, private sectors, such as the weaving and coal-mining industries, adopted steam power (Minami, 1979). As illustrated in Figure A2, by 1900, steam engines accounted for nearly 90% of the total horsepower used in the manufacturing sector.

Despite the significant shift from human power and water wheels to steam engines, the high fixed costs associated with steam engine adoption created barriers to their widespread use. As Minami (1979) highlights, implementing steam engines not only complicated production processes but also required more extensive and robust workshops. An inability to transmit power over long distances necessitated the centralization of machines in specific locations, leading to the factory system where machines were grouped together (*group drive system*). In this production system, power generated by steam engines was transmitted via shafts and belts affixed to the roof. Figure A3 illustrates an ironworks factory powered by steam engines, showing a giant steam engine, long shafts, and roof-mounted belts. This production system required sizable and sturdy workshops, significantly increasing the fixed costs of establishing steam-powered factories.

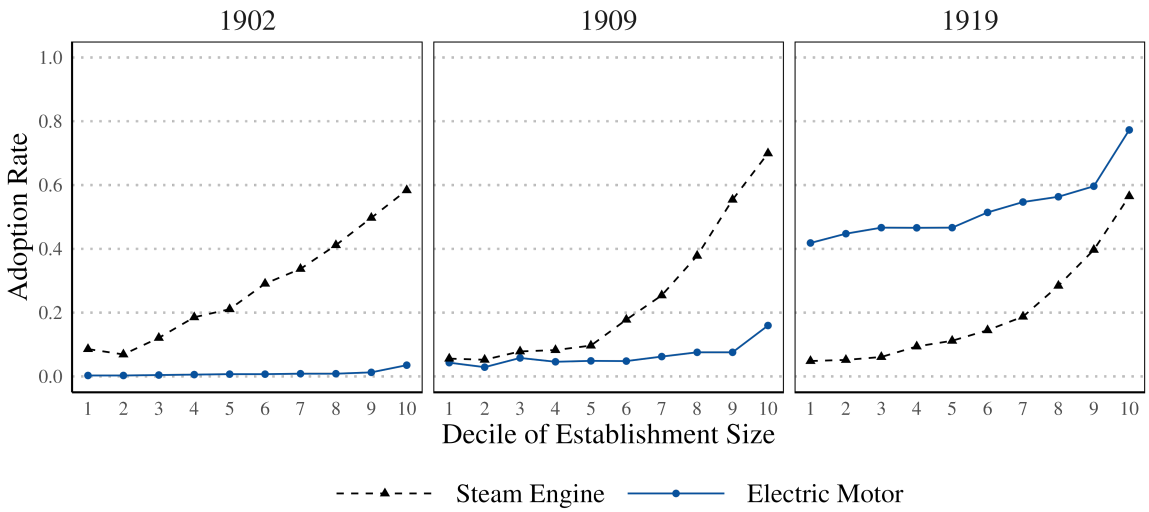
In contrast, electricity offered greater flexibility, as it could be easily transmitted to distant machines through electric cables, allowing for the installation of smaller electric motors. This salient advantage of electric motors facilitated the organization of production systems, called the *unit drive system*. Unlike steam engines that required extensive and complex workshops, this new production system enabled factories to operate in simpler and more compact spaces. According to Tanaka (1916), electric motors allowed for a reduction in workshop space to less than one-tenth of that needed for steam-powered factories. This anecdote suggests that establishing an electric-powered factory would entail significantly lower fixed costs, provided that an electric utility company supplied electricity.[9]

Figure 2 compares the adoption rates of steam engines and electric motors across various establishment sizes and different phases of electricity grid expansion, reinforcing the arguments

[8] In 1914, Inawashiro Hydro Power Co. successfully transmitted 37,500 kW of electricity from hydropower plants in Fukushima to Tokyo areas, which was 228 km long and the third longest transmission line in the world.

[9] Reichardt (2024) estimates the annualized cost of operating a 50-horsepower steam engine to be 3 to 4 times the annual wage of an unskilled worker, while the equivalent cost for an electric motor is only 2% of an unskilled worker's annual wage.

Figure 2: Technology Adoption by Establishment Size



Notes: These figures display the adoption rate of steam engines and electric motors by establishment size in 1902 (left), 1909 (center), and 1919 (right), where we define the number of workers as a measure of establishment size. Each point represents the average adoption rate among establishments in each decile bin. Note that the minimum number of workers is ten, and establishments in all manufacturing industries are included.
Source: Ministry of Agriculture and Commerce (1904, 1911, 1921)

and anecdotes introduced above. First, throughout all periods, smaller establishments were less likely to adopt steam engines. This suggests that the substantial fixed costs associated with steam engines likely discouraged smaller establishments from establishing steam-powered factories. Second, after the grid expansion (1909 and 1919), establishments began adopting electric motors regardless of their size.[10] This indicates that access to purchased electricity was crucial for most establishments, as it relieved them of the burden of generating their own power, thereby facilitating the broader adoption of electric motors. Consequently, by the middle phase of grid expansion in 1919, about half of the small and medium-sized establishments had adopted electric motors, suggesting the popularization of powered factories. These trends in adoption rates of steam engines and electric motors also apply within individual industries. Figure A4 provides examples of adoption rates for the textile and machinery industries.

2.2 *Data*

To investigate the effect of electricity access on manufacturing activities and population dynamics, I newly digitized various sources of official records and constructed a municipality-level dataset that covers the entirety of Japan. Table 1 lists the data sources used in this study, which I explain below.

[10] The high adoption rate of electric motors among the top decile of establishments across all periods suggests that only the largest establishments were able to generate electricity in-house to power their electric motors.

Table 1: Data Sources

Description	Data Source
Electricity supply information in 1909, 1914, 1919, 1924, and 1929	Ministry of Communications (1910, 1915, 1920, 1926, 1930)
Location of hydroelectric power stations in 1930	Ministry of Communications (1930)
Establishment information in 1902, 1909, 1916, and 1919	Ministry of Agriculture and Commerce (1904, 1911, 1918, 1921)
Population in 1908, 1913, 1918, 1920, 1925, 1930, and 1935	Bureau of Statistics (1908, 1913, 1918, 1920, 1925, 1930, 1935)
Firm information from 2012 to 2019	Orbis (2012-2019)
Hydropower potential, Streamflow	Arai et al. (2022)
Municipality boundary in 1920, ruggedness, coastal line, and railway stations	Ministry of Land, Infrastructure, Transport and Tourism (2024)
Municipality transition from 1900 to 2020	Higashide (2024)
Representative point of municipality	Center for Open Data in the Humanities (2024)

Spatial Units The spatial unit of analysis in this study is the municipality. While other studies on entire Japan have used prefectures or counties as the spatial unit (e.g., Tang, 2014; Yamasaki, 2023), analyzing at the municipality level provides a more granular understanding of the evolution of economic geography, which is particularly crucial when examining the persistent effects of a shock (Lin and Rauch, 2022). Given that there were some municipality merges and splits during the period of analysis (see Figure A5), I combined multiple data sources and successfully harmonized the municipality transitions from 1900 to 1940 (Center for Open Data in the Humanities, 2024; Higashide, 2024).[11] In all analyses throughout this paper, I use the harmonized municipality unit, which represents the most aggregated unit from 1900 to 1940.

Information on Electricity Supply To obtain information on electricity supply, I collected and digitized various issues of the Handbook of Electric Utility Industry (*Denki Jigyo Yoran*), published by the Ministry of Communications.[12] This publication, first released in 1908 (for the 1907 issue), contains municipality-level licensing information on electricity supply companies To align with the survey years of the Census of Manufactures, I constructed datasets for the years 1909, 1914, 1919, 1924, and 1929. Additionally, I digitized the locations of hydroelectric power stations over 2,000 kW in 1930 from the same source.

Establishment-Level Data I collected and digitized establishment-level information from the Factory Catalog (*Kojo Tsuran*), based on the Census of Manufactures and published by the Ministry of Agriculture and Commerce.[13] This official record covers establishments with over ten workers and includes information on the number of workers, horsepower by type of power source

[11] I also harmonized the municipality transitions from 1940 to 2020 for a validity check, although this was not used in the main analysis.

[12] Figure A6 shows a sample page from the Handbook of Electric Utility Industry.

[13] Okazaki et al. (2019) and Yamasaki (2023) also use this data source.

(e.g., water wheel, steam engine, electric motor), establishment date, address, and industry.[14] This series of official records includes 7,120 establishments in 1902, 14,175 in 1909, 17,540 in 1916, and 23,013 in 1919.

Population Municipality-level population data was obtained from several official records published by the Bureau of Statistics: the Table of Registered Population (*Nihon Teikoku Seitai Jinko Tokei*) in 1908, 1913, and 1918, and the Population Census in 1920, 1925, 1930, and 1935.

Firm-level Data for Long-run Analysis To examine the persistent effects on today's economic activities, I use firm-level data from Orbis. To exclude the effects of the Covid-19 pandemic, I restrict the sample period to 2012-2019. The dataset includes information on tax ID, postal code of headquarters, NACE Rev.2 industry code, employment, and sales. I drop observations without a postal code, industry code, tax ID, or at least one sales record between 2012 and 2019. Using postal codes, I link the firm addresses to the harmonized municipality unit I constructed. After excluding irrelevant samples, the analysis includes 1,195,319 unique firms.

Other Supplemental Data I define the center point of each municipality as its representative point, based on data obtained from Center for Open Data in the Humanities (2024). For geographical information, I downloaded 250m mesh data from Ministry of Land, Infrastructure, Transport and Tourism (2024) and calculated the average ruggedness for each municipality. In addition, I obtained coastal line and railway station locations from the same source and calculated the distance from each municipality center point to the nearest coastal line and railway station, respectively.

Summary Statistics Table A1 presents the summary statistics of the main variables used in this study. After harmonizing the municipalities, the number of municipalities included in the analysis is 10,429. The table shows the rapid expansion of the electricity grid in early 20th-century Japan: in 1909, only 4% of municipalities had electricity access, but this figure rose to 26% by 1914 and 93% by 1924. Also, the table indicates that in 1909, the steam engine was the most dominant power source, while the number of establishments using electric motors was relatively small.

3 Empirical Strategy

This section outlines the methodology used to identify the causal effect of electricity access on regional economic activities. To begin, I introduce hydropower potential as an instrumental variable for electricity access (Subsection 3.1). Next, I present two sets of evidence that motivate the identification strategy (Subsection 3.2). The first evidence is that hydropower potential drives the

[14] Ministry of Agriculture and Commerce (1911) covers establishments with over five workers, so I excluded those with fewer than nine workers from the analysis for consistency.

construction of hydropower stations, facilitating early access to electricity. The second one is that hydropower potential influences manufacturing activities only after the expansion of electricity grids. Together, these facts reinforce the assumptions of exclusion restriction and relevance condition required for the validity of the instrument.

3.1 *IV: Hydropower potential*

This paper employs municipalities' hydropower potential, based on natural geographical characteristics, as an instrumental variable for electricity access. As described in the historical background section, the expansion of electricity grids in early 20th-century Japan was predominantly driven by hydropower generation. Therefore, hydropower potential is expected to be a plausible predictor of electricity access. Specifically, I employ the hydropower potential of *run-of-river* hydroelectric power generation as the instrument. Unlike storage hydroelectric systems that require large reservoirs, such as dams, run-of-river hydroelectricity harnesses the natural flow of rivers. Because this method requires less infrastructure investment and is well-suited to Japan's topography—characterized by mountainous terrain and fast-flowing rivers—it became widespread during the early 20th century (Kurihara, 1964).

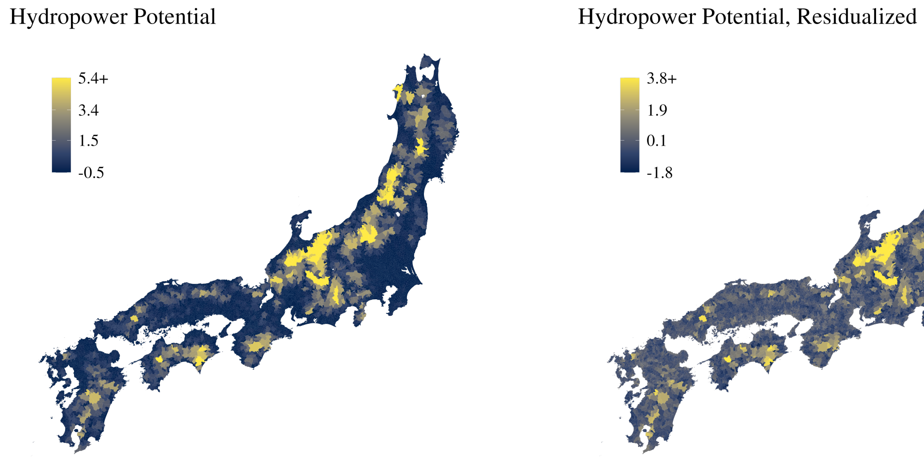
In line with the hydraulic engineering literature (Basso and Botter, 2012; Müller et al., 2014; Arai et al., 2022), the theoretical hydropower potential of run-of-river hydroelectric power generation in each basin j is calculated as the product of the water volume and the hydraulic head height of the basin:

$$\text{Hydropower Potential}_j = \text{Water Volume Index}_j \times \text{Hydraulic Head Height}_j. \tag{1}$$

In Equation (1), Water Volume Index$_j$ is defined as the cumulative annual flow volume of basin j. [15] Additionally, Hydraulic Head Height$_j$ is calculated as the difference between the minimum elevation of basin j and the minimum elevation within a 1 km radius. Due to the lack of detailed streamflow data across Japan, I rely on the estimated streamflow data calculated by Arai et al. (2022) to measure hydropower potential. Arai et al. (2022) developed a neural network model that uses natural geographical characteristics, such as precipitation, temperature, and elevation from gauged basins, as training data to predict streamflow for small-sized basins (approximately 10 km^2) throughout Japan. Given the potential influence of modern infrastructure, such as upstream dams or hydropower stations, on streamflow, Arai et al. (2022) excluded basins affected by these

[15] Specifically, Water Volume Index$_j$ is measured as the cumulative annual flow up to the 95th highest daily flow in a year. The design discharge (Q_D), which represents the Dth highest daily flow in a year, determines the optimal turbine size (Gernaat et al., 2017). Setting Q_D to about the 95th highest daily flow (i.e., Q_{95}) is generally regarded as a suitable criterion when calculating hydropower potential (Kao et al., 2014). Note that Water Volume Index$_j$ defined here corresponds to the cumulative water volume available for energy production when the design streamflow is set to be Q_{95}.

Figure 3: Geographical Distribution of Hydropower Potential



Notes: These maps illustrate the geographical distribution of the estimated hydropower potential at the municipality level, standardized with a mean of zero and a standard deviation of one. The left panel displays the distribution of *raw* hydropower potential, while the right panel shows the distribution of *residualized* hydropower potential after controlling for baseline municipality characteristics. These characteristics include area size (in log), distance to the coast (in log), distance to the nearest metropolis (in log), population density in 1908 (in log), streamflow, ruggedness, and prefecture fixed effects.
Source: Arai et al. (2022)

factors from their training data.

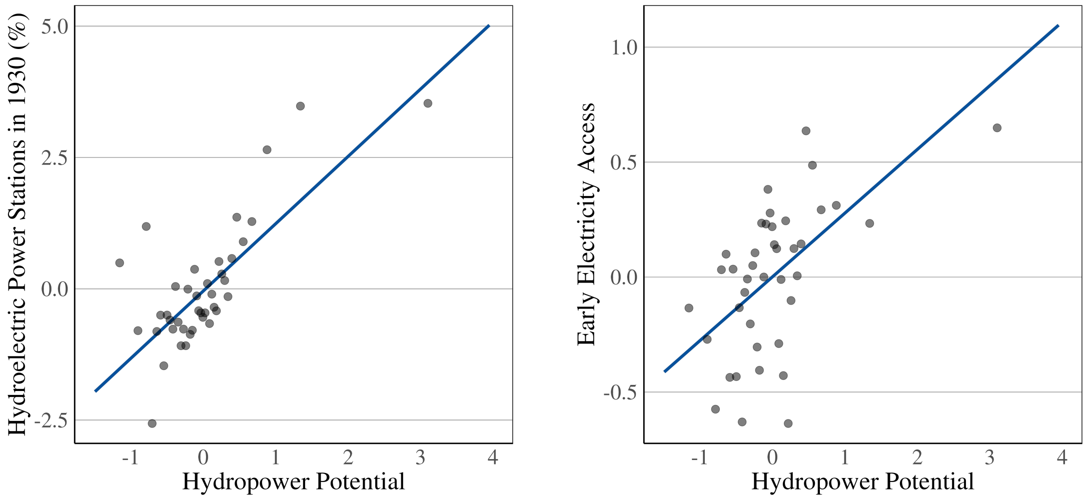
I calculated the hydropower potential at the municipality level by maximizing the potential of all basins within each municipality. Figure 3 illustrates the spatial distribution of the hydropower potential. The left panel displays the *raw* hydropower potential, while the right panel shows the *residual* hydropower potential after controlling for baseline municipality characteristics, such as area size, ruggedness, and streamflow. Although the potential tends to be higher in the Chubu region, where the Japanese Alps are located, municipalities with high hydropower potential are dispersed throughout the country. In addition, some mountainous areas, such as the eastern Fukushima and Chugoku regions, exhibit lower hydropower potential, confirming that the variations in this index stem from the interaction of water volume and hydraulic head height.

3.2 *Validity of the instrument*

The higher hydropower potential, the earlier electricity access

The underlying rationale of using hydropower potential as an instrumental variable for electricity access is that hydropower potential leads to electricity access through the construction of hydropower stations. Figure 4 supports this relevance condition. The panels of Figure 4 display a binned scatter plot showing the relationship between hydropower potential, the probability of having hydroelectric power stations in 1930, and the timing of electricity access, with val-

Figure 4: Hydropower Potential, Hydroelectric Generation, and Early Electricity Access



Notes: These panels show the binned scatter-plots between the hydropower potential and the probability of having hydroelectric power stations over 2,000 kW capacity in 1930 (left) and the timing of electricity access, defined as 1929 minus the year of the first electricity access (right). The unit of observation is the municipality where the electricity supply began after 1909. "Hydropower Potential" is a standardized measure of municipality-level potential for hydropower generation, with standard deviation of one. All values are residualized by controlling for the baseline municipality characteristics: the area size (in log), the distance to the coast (in log), the distance to the metropolis (in log), population density in 1908 (in log), streamflow, ruggedness, and prefecture fixed effects. The solid lines present the linear approximation of the relationship.

ues residualized by controlling for baseline municipality characteristics. The left panel shows a positive relationship, indicating that municipalities with higher hydropower potential were more likely to host hydroelectric power stations. In addition, the positive relationship in the right panel suggests that municipalities with greater hydropower potential gained electricity access earlier. These results are robust to controlling for streamflow and ruggedness (see Table A3). These findings confirm that hydropower potential is a strong predictor of earlier electricity access.

Hydropower potential matters only after the grid expansion

The other key identification assumption when using hydropower potential as an instrument is that hydropower potential affects manufacturing activities only through its impact on electricity access, conditional on local municipality characteristics (e.g., ruggedness, streamflow, and population density). To support this exclusion restriction assumption, I investigate the timing of when hydropower potential began to influence manufacturing activities. If hydropower potential only affected manufacturing activities after the expansion of electricity grids, it would confirm that the instrument is exogenous to preexisting economic factors driving manufacturing growth.

To examine the relationship between hydropower potential and manufacturing activities, I employ the following specification:

$$\begin{aligned} \text{Y}_{it} = & \sum_{t \neq 1909} \beta_t \text{ Hydropower Potential}_i \times \mathbf{1}\{\text{Year} = t\} + \\ & \sum_{t \neq 1909} \lambda_t \ \ln(\text{PopDens}_{i,1908}) \times \mathbf{1}\{\text{Year} = t\} + \\ & \sum_{t \neq 1909} \gamma_t \text{ Geography}_i \times \mathbf{1}\{\text{Year} = t\} + \alpha_i + \delta_t + \upsilon_{it}, \end{aligned} \tag{2}$$

where i and $t \in \{1902, 1909, 1916, 1919\}$ denote the municipality and year, respectively. To make the interpretation of the coefficients straightforward, I restrict the sample to municipalities where electricity access began after 1909. The outcome variable of interest, Y_{it}, represents the number of manufacturing establishments in municipality i in year t.[16] The main explanatory variable, Hydropower Potential$_i$, is a standardized measure of the municipality's potential for run-of-river hydropower generation, with a mean of zero and a standard deviation of one. To estimate the time path of how hydropower potential influenced manufacturing activities, I interact the hydropower potential with binary indicators for each year, using 1909 as the reference year. Since the expansition of electricity grid was predominantly driven by hydropower generation starting around 1907 (see Figure A1), and I exclude municipalities that gained electricity access before 1909, it is expected that hydropower potential would affect manufacturing activities only after 1909. The specification includes the municipality fixed effects (α_i) and year fixed effects (δ_t). Additionally, the model allows pre-electricity access population density and geographical characteristics—such as area size, distance to the coast, and distance to the nearest metropolis—to have a time-varying effect on the outcome. The former ensures that the population convergence or divergence pattern do not drive the results.[17] The latter helps to avoid misinterpreting the effects of advancements in international trade and urbanization as those of hydropower potential. Standard errors are clustered at the municipality level to account for serial correlation. Each coefficients, β_j, estimates the increase in the number of establishments caused by higher hydropower potential in a given year, j, relative to 1909.

Table 2 presents the estimation results. Columns (1)-(3) display the effect of hydropower potential on the total number of establishments, while Columns (4)-(6) focus specifically on establishments using electric motors. Consistent with the historical expansion of electricity grids, driven by hydropower generation beginning around 1907, I find that municipalities with higher

[16] Since many municipalities records zero establishments, the outcome variable is not log-like transformed, such as $\log(Y+1)$ or $\text{arcsinh}(Y)$, to avoid sensitivity to unit changes (Chen and Roth, 2023).

[17] While the literature documents a negative correlation between past population size and subsequent population growth in pre-modern economies (e.g., Dittmar, 2011; Glaeser et al., 2014), other studies find that larger cities grow more rapidly when located near railroads (Bogart et al., 2022; Yamasaki, 2023). Thus, it is ambiguous *ex ante* in which direction population density affects regional economic activities, such as population and manufacturing growth.

Table 2: Hydropower Potential and Manufacturing Activities

	Number of Establishments					
	Total			w/ Electric Motor		
	(1)	(2)	(3)	(4)	(5)	(6)
Hydropower Potential × 1902	-0.024	-0.020	-0.004	-0.001	-0.001	-0.001
	(0.022)	(0.023)	(0.023)	(0.001)	(0.001)	(0.001)
Hydropower Potential × 1916	0.015	0.023	0.018	0.047***	0.044***	0.040***
	(0.016)	(0.016)	(0.017)	(0.007)	(0.007)	(0.008)
Hydropower Potential × 1919	0.091**	0.090**	0.080**	0.101***	0.093***	0.081***
	(0.036)	(0.037)	(0.038)	(0.014)	(0.013)	(0.013)
Municipality FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Geography × Year FE	✓	✓	✓	✓	✓	✓
Pop. density 1908 × Year FE	✓	✓	✓	✓	✓	✓
Streamflow × Year FE		✓	✓		✓	✓
Ruggedness × Year FE			✓			✓
Observations	40,020	40,020	40,020	40,020	40,020	40,020
Adjusted R^2	0.68	0.68	0.68	0.34	0.34	0.34
Mean of dep.var	0.72	0.72	0.72	0.13	0.13	0.13

Notes: Observations are municipalities where the electricity supply began after 1909. Robust standard errors clustered at the municipality level are reported in parentheses. The dependent variable "Total" and "w/ Electric Motor" represent the total number of establishments and the number of establishments using electric motors, respectively. The independent variable, "Hydropower Potential", is a standardized measure of municipality-level potential for hydropower generation, with standard deviation of one, thus the estimates reflect differences in economic activities with one standard deviation higher hydropower potential. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

hydropower potential experienced larger increase in the number of establishments only from 1916 onward, with no significant effects observed between 1902 and 1909. In all columns, the impact of hydropower potential becomes more pronounced after 1909, and the effects are statistically significant after 1916 for establishments with electric motors and after 1919 for the total number of establishments. Furthermore, as Table 2 indicates, these results are robust to controlling for time-varying trends in streamflow and ruggedness, suggesting that the hydropower potential, the interaction between streamflow and ruggedness, plays a crucial role in driving manufacturing activities after the expansion of electricity gird.

Overall, there is a consistent absence of pre-trends, and a consistent effect of hydropower potential on manufacturing growth after 1916. These findings indicates that hydropower potential provides a plausible means to obtain variation in electricity access that is exogenous to preexisting economic determinants of manufacturing growth. Moreover, to address concerns that hydropower potential may have led to the use of water wheels prior to the expansion of electricity grids (Hornbeck et al., 2024), which could have influenced manufacturing activities after grid expansion, I verify that hydropower potential has no significant effect on the number of establishments using water wheels before and after the grid expansion (see Table A2).

4 Result: Short-run effect

In this section, I analyze the short-run impact of electricity access on manufacturing activities. After outlining the baseline specification, Subsection 4.1 presents the estimation results, demonstrating that electricity access significantly boosted manufacturing activities. Additionally, a series of robustness checks confirms that these effects were not influenced by preexisting regional characteristics or other confounding factors, such as railway access or infrastructure investments (Subsection 4.2). Lastly, Subsection 4.3 documents that the increase in manufacturing activities was primarily driven by new entrants, particularly those adopting electric motors.

4.1 *Main result*

To estimate the short-run effect of electricity access on manufacturing activities, I examine the extent to which electricity access in 1914 affected manufacturing activities between 1909 and 1919. The main specification is as follows:

$$\Delta \mathrm{Y}_{ip} = \eta \, \text{Electricity Access}_{i,1914} + \theta \, \ln(\text{PopDens}_{i,1908}) + \pi \, \text{Geography}_i + \tau_p + \varepsilon_{ip}, \tag{3}$$

where i and p express the municipality and prefecture, respectively. Y_{ip} represents changes in manufacturing activities, such as the number of establishments and manufacturing employment, between 1909 and 1919.[18] Electricity $\text{Access}_{i,1914}$ is a dummy variable indicating whether the municipality had electricity access in 1914. Thus, the coefficient of interest, η, captures the effect of electricity access in 1914 on manufacturing activities between 1909 and 1919. Control variables include population density in 1908, $\ln(\text{PopDens}_{i,1908})$, and a set of local geographic characteristics, Geography_i. Prefecture fixed effects, τ_p, account for prefecture-specific trends. I also estimate Conley (1999) standard errors, which adjust for spatial correlation across municipalities, assuming that municipalities are independent beyond a 30 km distance cutoff. To simplify the interpretation of coefficients, the sample is restricted to municipalities that gained electricity access after 1909.

Given that private electric utility companies were responsible for supplying electricity in early 20th-century Japan, it is possible that local demand factors drive the expansion of electricity supply. To address this potential endogeneity, I use hydropower potential, as introduced in Section 3, as an instrumental variable for electricity access in 1914. Columns (1)-(3) of Table A3 present the first-stage estimates, showing that a one standard deviation increase in hydropower potential

[18] Since many municipalities report zero establishments, the outcome variable is not log-transformed to avoid sensitivity to unit changes (Chen and Roth, 2023).

Table 3: Main results: Effect of Electricity Access on Industrialization

	Δ Number of Establishments (1909-1919)				Demographics	
	Total	w/ Electric Motor	Total	w/ Electric Motor	Δ Mnf. Workers (1909-1919)	Δ Pop. (1908-1918)
	(1)	(2)	(3)	(4)	(5)	(6)
Electricity Access in 1914	0.307***	0.559***	2.00**	1.29***	121.7***	165.6
	(0.090)	(0.064)	(1.02)	(0.404)	(43.3)	(371.8)
Model	OLS	OLS	IV	IV	IV	IV
Prefecture FE	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓	✓
Observations	10,005	10,005	10,005	10,005	10,005	9,991
First stage F-stat			65.9	65.9	65.9	66.7
Mean of dep.var	0.30	0.36	0.30	0.36	24.7	228.1

Notes: Second stage estimates are reported. Observations are municipalities where the electricity supply began after 1909. Estimates are from instrumental variables specifications in which the endogenous variable is "Electricity Access in 1914" and the instrument is the "Hydropower Potential". Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

is associated with a 4.1% higher likelihood of electricity access in 1914. This result holds even after controlling for natural geographic characteristics, such as streamflow and ruggedness. The F-statistic for the first stage is 65.9.

Table 3 presents the estimation results of the baseline specification. Across all OLS and IV specifications, the effect of electricity access on changes in manufacturing activities is positive, substantial, and statistically different from zero. There are two noteworthy results in Table 3. First, as shown in column (3), electricity access led to an increase of two establishments per municipality, which is approximately 6.6 times larger than the average increase. In addition, as column (4) shows, it also stimulated the adoption of electric motors. Second, columns (5) and (6) indicate that electricity access led to a significant increase in the number of manufacturing workers but had no effect on population growth. These results suggest that the increase in manufacturing employment was driven by those who started to engage in the manufacturing sector, rather than by an influx of workers from other municipalities.

Comparing the OLS and IV estimates in Table 3, we observe that the IV estimates of the effects of electricity access are substantially larger than the OLS estimates. Two potential reasons could explain this downward bias in the OLS estimates relative to the IV estimates, both of which are related to the compliers in the IV strategy. First, the difference between the OLS and IV estimates may be driven by imbalanced industry composition. Due to the construction of hydropower potential, municipalities with higher potential are often located in mountainous areas where small-scale industries, such as textiles and food manufacturing, are prevalent. In contrast, large-scale industries like steel, machinery, and chemical manufacturing tend to be located in flat, coastal regions to minimize transportation costs. As a result, the compliers in the IV strategy may represent regions with more small-scale industries compared to the OLS sample, leading to larger estimates.[19] Second, differences in the initial development levels of the municipalities may also contribute to the gap between the OLS and IV estimates. Since the compliers in the IV strategy are likely located in less developed regions, they may have more room for manufacturing growth.

4.2 *Robustness*

In order for the estimates presented in Subsection 4.1 to be valid, it is essential to ensure that the results are not influenced by (i) unobserved preexisting regional characteristics and (ii) time-varying confounding factors that emerged after the expansion of the electricity grid. To address these concerns, I perform a series of robustness checks.

Placebo test I begin by addressing the concern that municipalities that gained electricity access in 1914 may have followed a different trajectory in manufacturing activities, possibly due to their suitability for water wheel use. Although Subsection 3.2 confirms that hydropower potential had no significant effect on manufacturing activities before the expansion of the electricity grid, I conduct a placebo test to further allays concerns about identification. In this test, shown in Table 4, the dependent variable is replaced with changes in manufacturing activities between 1902 and 1909, while the treatment variable remains a dummy indicating electricity access in 1914. The results in Table 4 show that, across all specifications, the point estimates on lagged values of manufacturing activities are much smaller than those in the main specification and statistically insignificant.

Railway Access It is possible that increased market size due to improved railway access stimulated manufacturing activities and the adoption of electric motors (Yamasaki, 2023). Since private railroad companies were, in some cases, responsible for electricity supply, railway access could bias the estimates upward. To address this concern, I include the change in the distance to the nearest railway station between 1909 and 1919 as an additional control, which captures increased railway access. The results in Table A4 show that the point estimates are nearly identical to those in the main specification and remain statistically different from zero, suggesting that the results are not driven by increased railway access.

[19] Additionally, Glaeser et al. (2015) document that industries with significant returns to scale, such as steel, can dampen entrepreneurial activities in a region.

Table 4: Falsification: Effect of Electricity Access on Industrialization

	Δ Number of Establishments (1902-1909)				Demographics
	Total	w/ Electric Motor	Total	w/ Electric Motor	Δ Mnf. Workers (1902-1909)
	(1)	(2)	(3)	(4)	(5)
Electricity Access in 1914	0.395***	0.004**	0.176	0.012	24.4
	(0.083)	(0.002)	(0.693)	(0.016)	(28.0)
Model	OLS	OLS	IV	IV	IV
Prefecture FE	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓
Observations	10,005	10,005	10,005	10,005	10,005
First stage F-stat			65.9	65.9	65.9
Mean of dep.var	0.33	0.004	0.33	0.004	10.5

Notes: Second stage estimates are reported. Observations are municipalities where the electricity supply began after 1909. Estimates are from instrumental variables specifications in which the endogenous variable is "Electricity Access in 1914" and the instrument is the "Hydropower Potential". Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Infrastructure Investment Another potential explanation is that infrastructure investment, such as the construction of dams, spurred manufacturing activities (Kline and Moretti, 2014; Leknes and Modalsli, 2020; Severnini, 2022). Although run-of-river hydroelectric power generation, which is the target of the hydropower potential used as the instrument, does not require large reservoirs, it could still be associated with substantial infrastructure investment. However, Table A5, which excludes municipalities hosting hydropower plants with a capacity over 2,000 kW in 1930, suggests that this is unlikely.[20] The point estimates become slightly smaller but remain statistically significant, indicating that the results are not primarily driven by infrastructure investment.

4.3 *Mechanism*

I hypothesize that electric motors powered by purchased electricity, with their significantly lower fixed costs compared to steam engines, can reduce barriers to entry in the manufacturing sector with powered factories. Given that this argument aligns with historical anecdotes and descriptive evidence presented in Subsection 2.1, we would expect *new entrants* to be the primary contributors to the increase in manufacturing activities. I test this hypothesis by isolating the effect of

[20]Since most hydroelectric power stations had a capacity below 2,000 kW, this subsample analysis is compatible with the relevance condition of the IV strategy.

Table 5: Mechanism: Effect of Electricity Access on Entrant Activities (1909-1919)

	Number of Establishments						Demographics	
	Total		w/ Steam Engine		w/ Electric Motor		Mnf. Workers	
	(1) Δ All	(2) Entrant	(3) Δ All	(4) Entrant	(5) Δ All	(6) Entrant	(7) Δ All	(8) Entrant
Electricity Access in 1914	2.00**	2.69***	0.277	0.273	1.29***	0.909***	121.7***	105.3***
	(1.02)	(0.858)	(0.215)	(0.170)	(0.404)	(0.265)	(43.3)	(37.5)
Model	IV	IV	IV	IV	IV	IV	IV	IV
Prefecture FE	✓	✓	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓	✓	✓	✓
Observations	10,005	10,005	10,005	10,005	10,005	10,005	10,005	10,005
First stage F-stat	65.9	65.9	65.9	65.9	65.9	65.9	65.9	65.9
Mean of dep.var	0.30	0.58	0.05	0.14	0.36	0.23	24.7	28.3

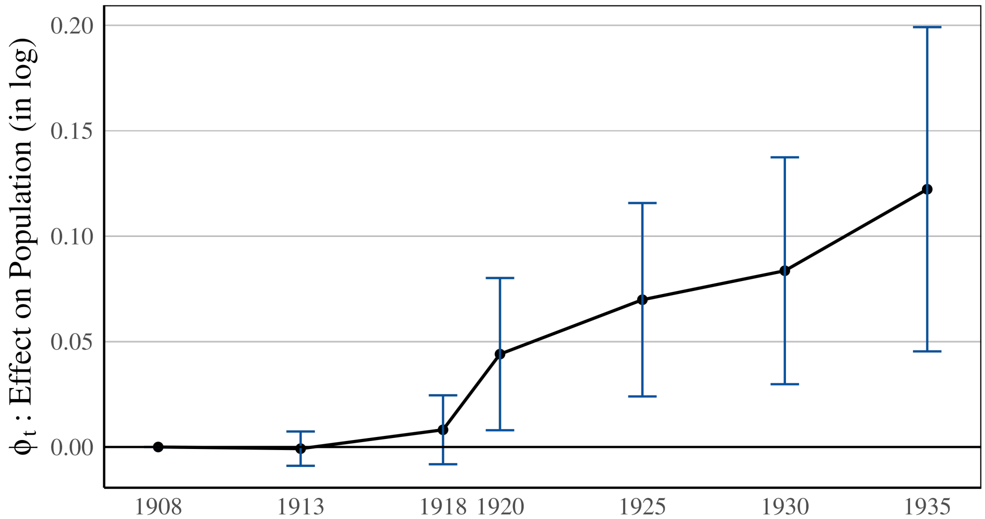
Notes: Second stage estimates are reported. Observations are municipalities where the electricity supply began after 1909. Estimates are from instrumental variables specifications in which the endogenous variable is "Electricity Access in 1914" and the instrument is the "Hydropower Potential". Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

new entrants from the baseline specification (Table 5).

Table 5 presents the results, where "Entrant" is defined as an establishment that began operating between 1909 and 1919.[21] The odd columns show the effects I introduced in Table 3 and the even columns present the effects of new entrants. Three key findings emerge from the analysis. First, comparisons between columns (1) and (2) suggest that electricity access not only stimulated the entry of new establishments but also encouraged exits (2.69-2.00), implying a within-sector reallocation. Second, while there are no significant impacts on the adoption of steam engines (columns (3)-(4)), the effect on entrants adopting electric motors is about 0.9 and statistically significant, accounting for 70% of the total effect (columns (5)-(6)). Finally, columns (7)-(8) show that the increase in manufacturing workers was mainly driven by new entrants, with 87% of the total effect attributable to the increase in workers employed by new entrants. Overall, these findings support the hypothesis that the reduction in fixed costs associated with electric motor use stim-

[21] More specifically, I decompose the effects of the main results as follows: Δ(# establishments) = (# entrants) − (# exits), Δ(# establishments with technology) = Δ(# incumbents with technology) + (# entrants with technology) − (# exits with technology), Δ(# workers) = Δ(# workers employed by incumbents) + (# workers employed by entrants) − (# workers employed by exits), where *entrants*, *incumbents*, and *exits* refer to establishments founded between 1909 and 1919, those continuing to operate in both 1909 and 1919, and those that ceased operations between 1909 and 1919, respectively. Note that the records only include establishments with at least ten workers.

Figure 5: Effect on Population Growth in Early 20th Century



Notes: Second stage estimates of ϕ_t are reported. Observations are municipalities where the electricity supply began after 1909. Estimates are from instrumental variables specifications in which the endogenous variable is "Early Electricity Access" and the instrument is the "Hydropower Potential". The control variables include the municipality area size (in log), the distance to the coast (in log), the distance to the metropolis (in log), population density in 1908 (in log), streamflow, ruggedness, and prefecture fixed effects. Robust standard errors are clustered by municipalities within 30km radius, following Conley (1999). Confidential intervals are calculated at the 95% level. Note that number of observations is 9,950 and the first stage F-statistic is 22.2.

ulated new entrant activity, particularly among those adopting electric motors, and contributed to the increase in manufacturing employment. Table A6 presents the falsification test for these results. While there are positive effects on the number of entrants and the workers employed by them, these effects are considerably smaller than the estimates in Table 5.

5 Result: Long-run effect

5.1 *Population Dynamics*

A technological shock can have a long-run impact on regional growth (Alesina et al., 2013; Dittmar, 2011; Yamasaki, 2023; Kitamura, 2022). In particular, technological shocks in the manufacturing sector can accumulate over time, in contrast to those in the agricultural sector (Desmet and Rossi-Hansberg, 2009; Michaels et al., 2012). Therefore, regions that experience technological change earlier have the opportunity to accumulate more technical knowledge than others, leading to higher manufacturing wages and increased migration. This process also makes it difficult for lagging regions to expand manufacturing activities and catch up with leading regions due to the technological gap and the agglomeration forces within the manufacturing sector.

Motivated by this argument, I examine whether the regional advantages of achieving technological change earlier influence the subsequent trajectory of regional development. The technical change from steam engines to electric motors profoundly transformed the power sources of manufacturing activities, making this technical shock a unique opportunity to study the long-run impact of technical change on regional development. To investigate the impact of the population dynamics, I estimate the following model:

$$\ln\left(\frac{\text{Population}_{it}}{\text{Population}_{i,1908}}\right) = \phi_t \text{Early Electricity Access}_i + \kappa_t \ \ln(\text{PopDens}_{i,1908}) + \xi_t \ \text{Geography}_i + \varsigma_{pt} + \epsilon_{ipt}, \tag{4}$$

where i, p, and t represent the municipality, prefecture, and year, respectively, I estimate the regressions separately for each year-pair, such as analyzing changes from 1908 to 1913 using only data from those years. This approach avoids the interpretation challenges associated with regression models that pool data across multiple time periods (e.g., Roth et al., 2023). The dependent variable is the population growth between 1908 and t. The main explanatory variable, Early Electricity Access$_i$, is defined as 1929 minus the year of first electricity access, assigning a higher value to municipalities with earlier access.[22] Thus, ϕ_t captures the effect of one year earlier electricity access on population growth between 1908 and year t. Given the potential endogeneity of the timing of electricity access, I use hydropower potential as an instrumental variable for early electricity access.

Figure 5 presents the second-stage estimates of ϕ_t, representing the dynamic effect of early electricity access on population growth. While there is a sizable short-run impact on manufacturing activities, as discussed in Section 4, the short-run effect on population growth is small and statistically insignificant. However, the impact of early electricity access on population growth becomes gradually more pronounced over time, leading to over a 10% increase in population growth by 1935. This result, combined with the findings in Section 4, suggests that municipalities that experienced technical change earlier expanded manufacturing activities, leading to higher wages and agglomeration in the manufacturing sector. As a result, these municipalities attracted more economic activities, leading to a lasting advantage in subsequent regional development. This disparity in regional growth induced by the timing of technical change implies that agglomeration forces in manufacturing sector might have impeded industrialization in other regions.

5.2 *Today's Economic Activities*

Next, I examine the persistent effects of early electricity access. Using firm-level data from Orbis (2012-2019), I estimate the impact of early electricity access on today's economic activities, using hydropower potential as an instrument. Table 6 presents the second-stage estimates. The results

[22] Note that I only digitized information on the year of first electricity access up to 1929 every five years (i.e., 1909, 1914, 1919, 1924, and 1929). Thus, Early Electricity Access$_i$ takes only five values: 20, 15, 10, 5, and 0.

Table 6: Effects of Early Electricity Access on Today's Economic Activities (in log)

	Num. of Firms		Num. of Emp.		Ave. Sales		Sales/Emp.	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Early Electricity Access	0.057***	0.158*	0.066***	0.185*	0.024***	0.095*	0.010***	0.067*
	(0.004)	(0.084)	(0.005)	(0.103)	(0.003)	(0.054)	(0.002)	(0.039)
Model	OLS	IV	OLS	IV	OLS	IV	OLS	IV
Prefecture FE	✓	✓	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓	✓	✓	✓
Observations	9,852	9,852	9,474	9,474	9,852	9,852	9,474	9,474
First stage F-stat		26.4		29.6		26.4		29.6
Mean of dep.var	3.4	3.4	5.0	5.0	7.8	7.8	6.3	6.3

Notes: Second stage estimates are reported. Observations are municipalities where the electricity supply began after 1909. Estimates are from instrumental variables specifications in which the endogenous variable is "Early Electricity Access" and the instrument is the "Hydropower Potential". "Early Electricity Access" is defined as 1935 minus the year of the first electricity access. Robust standard errors clustered by municipalities within 30km radious, following Conley (1999), are reported in parentheses. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

indicate that municipalities with earlier electricity access have achieved higher levels of economic development even today: they have more firms, larger employment, higher average sales, and greater productivity measured by sales per employee. These findings suggest that the regional advantages of early technical change have persisted over time, leading to a lasting impact on economic activities even 100 years later.

6 Conclusion

Understanding how technological change progresses and impacts regional development is crucial in policy debates on economic growth. To shed light on these issues, this paper examines the transition from steam engines to electric motors in early 20th-century Japan and its effect on regional economic activities. Drawing from the historical context, I hypothesize that electric motors powered by purchased electricity, with their much lower fixed costs compared to steam engines, played a pivotal role in lowering barriers to entry in the manufacturing sector, thereby stimulating manufacturing activities.

To investigate this hypothesis, I exploit the historical expansion of electricity grids and newly digitized official records. To address the endogeneity of electricity access, I use hydropower potential as an instrumental variable, controlling for other regional characteristics. The results indicate that electricity access significantly increased manufacturing activities by stimulating the entry of new establishments. This finding underscores the importance of new entrants in driving technological change and manufacturing growth during the Second Industrial Revolution Moreover, I find that municipalities with earlier electricity access experienced greater population growth, resulting in a lasting advantage in subsequent regional development. Exploring the underlying mechanisms that drove this lasting impact presents an interesting avenue for future research.

References

Alesina, Alberto, Paola Giuliano, and Nathan Nunn, "On the Origins of Gender Roles: Women and the Plough," *The Quarterly Journal of Economics*, May 2013, *128* (2), 469–530.

Arai, Ryosuke, Yasushi Toyoda, and So Kazama, "Streamflow Maps for Run-of-River Hydropower Developments in Japan," *Journal of Hydrology*, April 2022, *607*, 127512.

Bakker, Jan David, Stephan Maurer, Jörn-Steffen Pischke, and Ferdinand Rauch, "Of Mice and Merchants: Connectedness and the Location of Economic Activity in the Iron Age," *The Review of Economics and Statistics*, August 2021, *103* (4), 1–14.

Basso, S and G Botter, "Streamflow Variability and Optimal Capacity of Run-of-river Hydropower Plants," *Water Resources Research*, October 2012, *48* (10).

Berkes, Enrico, Ruben Gaetani, and Martí Mestieri, "Technological Waves and Local Growth," *mimeo*, 2024.

Bernhofen, Daniel M and John C Brown, "A Direct Test of the Theory of Comparative Advantage: The Case of Japan," *Journal of Political Economy*, February 2004, *112* (1), 48–67.

_ and _ , "An Empirical Assessment of the Comparative Advantage Gains from Trade: Evidence from Japan," *American Economic Review*, February 2005, *95* (1), 208–225.

Bleakley, Hoyt and Jeffrey Lin, "Portage and Path Dependence," *The Quarterly Journal of Economics*, May 2012, *127* (2), 587–644.

Bogart, Dan, Xuesheng You, Eduard J Alvarez-Palau, Max Satchell, and Leigh Shaw-Taylor, "Railways, Divergence, and Structural Change in 19th Century England and Wales," *Journal of Urban Economics*, March 2022, *128* (103390), 103390.

Bosker, Maarten, Eltjo Buringh, and Jan Luiten van Zanden, "From Baghdad to London: Unraveling Urban Development in Europe, the Middle East, and North Africa, 800–1800," *The Review of Economics and Statistics*, October 2013, *95* (4), 1418–1437.

Braguinsky, Serguey, Atsushi Ohyama, Tetsuji Okazaki, and Chad Syverson, "Product Innovation, Product Diversification, and Firm Growth: Evidence from Japan's Early Industrialization," *American Economic Review*, December 2021, *111* (12), 3795–3826.

Bresnahan, Timothy F and M Trajtenberg, "General Purpose Technologies 'Engines of Growth'?," *Journal of Econometrics*, January 1995, *65* (1), 83–108.

Brezis, Elise S and Paul R Krugman, "Technology and the Life Cycle of Cities," *Journal of Economic Growth*, 1997, *2* (4), 369–383.

— **, P Krugman, and Daniel Tsiddon**, "Leapfrogging in International Competition: A Theory of Cycles in National Technological Leadership," *American Economic Review*, 1993, *83* (5), 1211–1219.

Bureau of Statistics, *Table of Registered Population (Nihon Teikoku Seitai Jinko Tokei)* 1908.

— , *Table of Registered Population (Nihon Teikoku Seitai Jinko Tokei)* 1913.

— , *Table of Registered Population (Nihon Teikoku Seitai Jinko Tokei)* 1918.

— , "Census of Population," 1920.

— , "Census of Population," 1925.

— , "Census of Population," 1930.

— , "Census of Population," 1935.

Burgess, Robin, Michael Greenstone, Nicholas Ryan, and Anant Sudarshan, "Electricity Demand and Supply on the Global Electrification Frontier," *mimeo*, 2023.

Burlig, Fiona and Louis Preonas, "Out of the Darkness and into the Light? Development Effects of Rural Electrification," *Journal of Political Economy*, September 2024, *132* (9), 2937–2971.

Center for Open Data in the Humanities, "Historical Administrative Boundary Dataset Beta Version," 2024.

Chen, Jiafeng and Jonathan Roth, "Logs with Zeros? Some Problems and Solutions," *The Quarterly Journal of Economics*, 2023.

Clay, Karen, Joshua Lewis, and Edson Severnini, "Canary in a Coal Mine: Infant Mortality and Trade-offs Associated with Mid-20th Century Air Pollution," *The Review of Economics and Statistics*, May 2024, *106* (3), 698–711.

Conley, T G, "GMM Estimation with Cross Sectional Dependence," *Journal of Econometrics*, September 1999, *92* (1), 1–45.

Davis, Donald R and David E Weinstein, "Bones, Bombs, and Break Points: The Geography of Economic Activity," *American Economic Review*, December 2002, *92* (5), 1269–1289.

— **and** — , "A Search for Multiple Equilibria in Urban Industrial Structure," *Journal of Regional Science*, January 2008, *48* (1), 29–65.

Desmet, Klaus and Esteban Rossi-Hansberg, "Spatial Growth and Industry Age," *Journal of Economic Theory*, November 2009, *144* (6), 2477–2502.

Dinkelman, Taryn, "The Effects of Rural Electrification on Employment: New Evidence from South Africa," *American Economic Review*, December 2011, *101* (7), 3078–3108.

Dittmar, Jeremiah E, "Information Technology and Economic Change: The Impact of the Printing Press," *The Quarterly Journal of Economics*, August 2011, *126* (3), 1133–1172.

Fried, Stephie and David Lagakos, "Electricity and Firm Productivity: A General-Equilibrium Approach," *American Economic Journal: Macroeconomics*, 2023.

Gaggl, Paul, Rowena Gray, Ioana Marinescu, and Miguel Morin, "Does Electricity Drive Structural Transformation? Evidence from the United States," *Labour Economics*, January 2021, *68*, 101944.

Gernaat, David E H J, Patrick W Bogaart, Detlef P van Vuuren, Hester Biemans, and Robin Niessink, "High-Resolution Assessment of Global Technical and Economic Hydropower Potential," *Nature Energy*, September 2017, *2* (10), 821–828.

Glaeser, Edward L, Giacomo A M Ponzetto, and Kristina Tobio, "Cities, Skills and Regional Change," *Regional Studies*, January 2014, *48* (1), 7–43.

_ , Sari Pekkala Kerr, and William R Kerr, "Entrepreneurship and Urban Growth: An Empirical Assessment with Historical Mines," *The Review of Economics and Statistics*, May 2015, *97* (2), 498–520.

Goldin, Claudia and Lawrence F Katz, "The Origins of Technology-Skill Complementarity," *The Quarterly Journal of Economics*, August 1998, *113* (3), 693–732.

Gordon, Robert, *The Rise and Fall of American Growth: The U.S. Standard of Living Since the Civil War*, Princeton: Princeton University Press, December 2017.

Hall, Bronwyn H, "Innovation and Diffusion," *NBER Working Paper Series*, 2004.

_ and Beethika Khan, "Adoption of New Technology," *NBER Working Paper Series*, 2003.

Hanlon, W Walker, "Temporary Shocks and Persistent Effects in Urban Economies: Evidence from British Cities after the U.S. Civil War," *The Review of Economics and Statistics*, March 2017, *99* (1), 67–79.

Higashide, "Municipality Transition Information," 2024.

Hornbeck, Richard, Shanon Hsu, Anders Humlum, and Martin Rotemberg, "Gaining Steam: Incumbent Lock-in and Entrant Leapfrogging," *NBER Working Paper Series*, April 2024.

Ichimura, Hidehiko, Yasuyuki Sawada, Yutaro Takayasu, and Mari Tanaka, "A Rise of New Elites? The Role of Secondary Schools in Early Development," *mimeo*, 2024.

Juhász, Réka, Shogo Sakabe, and David Weinstein, "Codification, Technology Absorption, and the Globalization of the Industrial Revolution," *NBER Working Paper Series*, July 2024.

Kao, Shih-Chieh, Ryan A Mcmanamay, Kevin M Stewart, Nicole M Samu, Boualem Hadjerioua, Scott T Deneale, Dilruba Yeasmin, M Fayzul K Pasha, Abdoul A Oubeidillah, and Brennan T Smith, "New Stream-Reach Development: A Comprehensive Assessment of Hydropower Energy Potential in the United States," Technical Report, Oak Ridge National Laboratory (ORNL) April 2014.

Kassem, Dana, "Does Electrification Cause Industrial Development? Grid Expansion and Firm Turnover in Indonesia," *Journal of Development Economics*, March 2024, *167* (103234), 103234.

Kawaguchi, Daiji, Tetsuji Okazaki, and Xuanli Zhu, "Factory Automation, Labor Demand, and Local Labor Market," *IZA Discussion Paper Series*, March 2024.

Kitamura, Shuhei, "Tillers of Prosperity: Land Ownership, Reallocation, and Structural Transformation," *OSF Preprints*, May 2022.

Kitchens, Carl and Price Fishback, "Flip the Switch: The Impact of the Rural Electrification Administration 1935-1940," *Journal of Economic History*, 2015, *75* (4), 1161–1195.

Kline, Patrick and Enrico Moretti, "Local Economic Development, Agglomeration Economies, and the Big Push: 100 Years of Evidence from the Tennessee Valley Authority," *The Quarterly Journal of Economics*, February 2014, *129* (1), 275–331.

Kurihara, Toyo, *Denryoku (Electric Utility)*, Tokyo: Kojunsha, 1964.

Lee, Kenneth, Edward Miguel, and Catherine Wolfram, "Experimental Evidence on the Economics of Rural Electrification," *Journal of Political Economy*, April 2020, *128* (4), 1523–1565.

Leknes, Stefan and Jørgen Modalsli, "Who Benefited from Industrialization? The Local Effects of Hydropower Technology Adoption in Norway," *Journal of Economic History*, March 2020, *80* (1), 207–245.

Lewis, Joshua, "Infant Health, Women's Fertility, and Rural Electrification in the United States, 1930–1960," *Journal of Economic History*, March 2018, *78* (1), 118–154.

__ **and Edson Severnini**, "Short- and Long-run Impacts of Rural Electrification: Evidence from the Historical Rollout of the U.S. Power Grid," *Journal of Development Economics*, March 2020, *143*, 102412.

Lin, Jeffrey and Ferdinand Rauch, "What Future for History Dependence in Spatial Economics?," *Regional Science and Urban Economics*, May 2022, *94*, 103628.

Lipscomb, Molly, A Mushfiq Mobarak, and Tania Barham, "Development Effects of Electrification: Evidence from the Topographic Placement of Hydropower Plants in Brazil," *American Economic Journal: Applied Economics*, April 2013, *5* (2), 200–231.

Michaels, G, F Rauch, and S J Redding, "Urbanization and Structural Transformation," *The Quarterly Journal of Economics*, May 2012, *127* (2), 535–586.

Minami, Ryoshin, *Doryoku Kakumei to Gijutsu Simpo - Senzen Seizoki no Bunseki (Power Source Revolution and Technological Progress)*, Tokyo: Sanseido, 1979.

Ministry of Agriculture and Commerce, *Factory Catalog, 1902 Edition* 1904.

__ , *Factory Catalog, 1909 Edition* 1911.

__ , *Factory Catalog, 1916 Edition* 1918.

__ , *Factory Catalog, 1919 Edition* 1921.

Ministry of Communications, *Denki Jigyo Yoran (Handbook of Electric Utility Industry)* 1910.

__ , *Denki Jigyo Yoran (Handbook of Electric Utility Industry)* 1915.

__ , *Denki Jigyo Yoran (Handbook of Electric Utility Industry)* 1920.

__ , *Denki Jigyo Yoran (Handbook of Electric Utility Industry)* 1926.

—, *Denki Jigyo Yoran (Handbook of Electric Utility Industry)* 1930.

—, *Denki Jigyo Yoran (Handbook of Electric Utility Industry)* 1938.

Ministry of Land, Infrastructure, Transport and Tourism, "National Land Numerical Information Download Service," 2024.

Molinder, Jakob, Tobias Karlsson, and Kerstin Enflo, "More Power to the People: Electricity Adoption, Technological Change, and Labor Conflict," *Journal of Economic History*, June 2021, *81* (2), 481–512.

Morck, Randall and Masao Nakamura, "Japan's Ultimately Unaccursed Natural Resources-Financed Industrialization," *Journal of the Japanese and International Economies*, March 2018, *47*, 32–54.

Mumford, Lewis, *Technics and Civilization*, London: Routledge, 1934.

Müller, Marc F, David N Dralle, and Sally E Thompson, "Streamflow Variability and Optimal Capacity of Run-of-river Hydropower Plants," *Water Resources Research*, July 2014, *50* (7), 5510–5531.

Okazaki, Tetsuji, Toshihiro Okubo, and Eric Strobl, "Creative Destruction of Industries: Yokohama City in the Great Kanto Earthquake, 1923," *Journal of Economic History*, March 2019, *79* (1), 1–31.

Redding, Stephen J, Daniel M Sturm, and Nikolaus Wolf, "History and Industry Location: Evidence from German Airports," *The Review of Economics and Statistics*, August 2011, *93* (3), 814–831.

Reichardt, Hugo, "Scale-Biased Technical Change and Inequality," *mimeo*, 2024.

Research Committee on Electric Utility Policy ed., *Denki Jigyo Hosei-shi (History of the Legal Framework for the Electlic Utility Industry)*, Denryoku Shinposha, 1965.

Rosenberg, Michele and F Curci, "Factory Location: Resistance to Technology Adoption and Local Institutions," *SSRN Electronic Journal*, 2023.

Roth, Jonathan, Pedro H C Sant'Anna, Alyssa Bilinski, and John Poe, "What's trending in difference-in-differences? A synthesis of the recent econometrics literature," *Journal of Econometrics*, August 2023, *235* (2), 2218–2244.

Rud, Juan Pablo, "Electricity provision and industrial development: Evidence from India," *Journal of Development Economics*, March 2012, *97* (2), 352–367.

Severnini, Edson, "The Power of Hydroelectric Dams: Historical Evidence from the United States over the Twentieth Century," *The Economic Journal*, December 2022, *133* (649), 420–459.

Sussman, Nathan and Yishay Yafeh, "Institutions, Reforms, and Country Risk: Lessons from Japanese Government Debt in the Meiji Era," *Journal of Economic History*, 2000, *60* (2).

Tanaka, Tatsuo, "Kojo Denryoku no Denka wo Unagasu (Promote the electrification of factory power)," *Denki no Tomo*, 1916, (402), 87–90.

Tang, John P, "Railroad Expansion and Industrialization: Evidence from Meiji Japan," *Journal of Economic History*, 2014, *74* (3), 863–886.

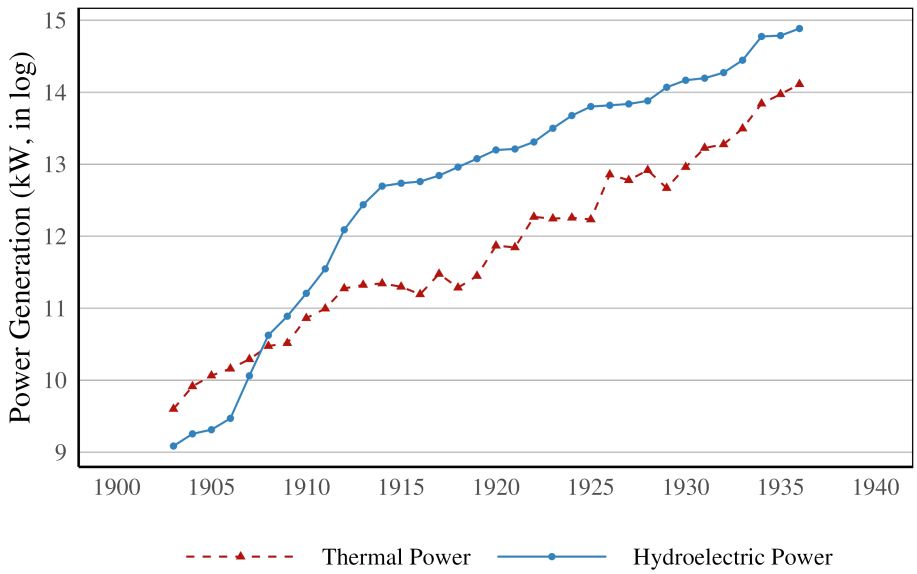
— **and Sergi Basco**, "Banks, Credit Supply, and the Life Cycle of Firms: Evidence from Late Nineteenth Century Japan," *Journal of Banking and Finance*, September 2023, *154* (106937), 106937.

Works, Ikegai Iron, *Ikegai Tekko Gojyu-nenn Shi (50-Year History of Ikegai Iron Works)* 1941.

Yamasaki, Junichi, "Railroads, Technology Adoption, and Modern Economic Development: Evidence from Japan," *SSRN Electronic Journal*, 2023.

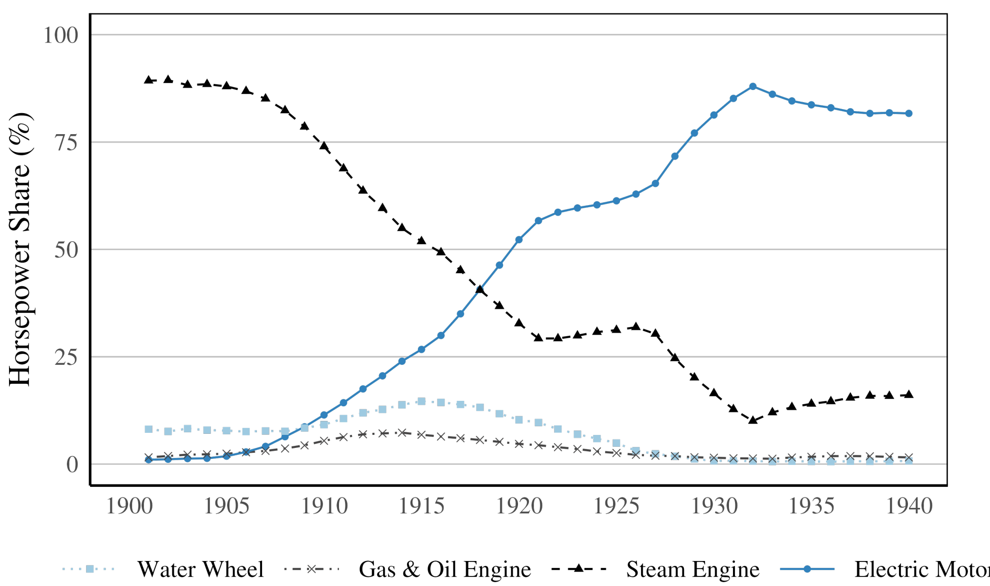
Appendix A Historical Background: Additional Details

Figure A1: Source of Power Generation



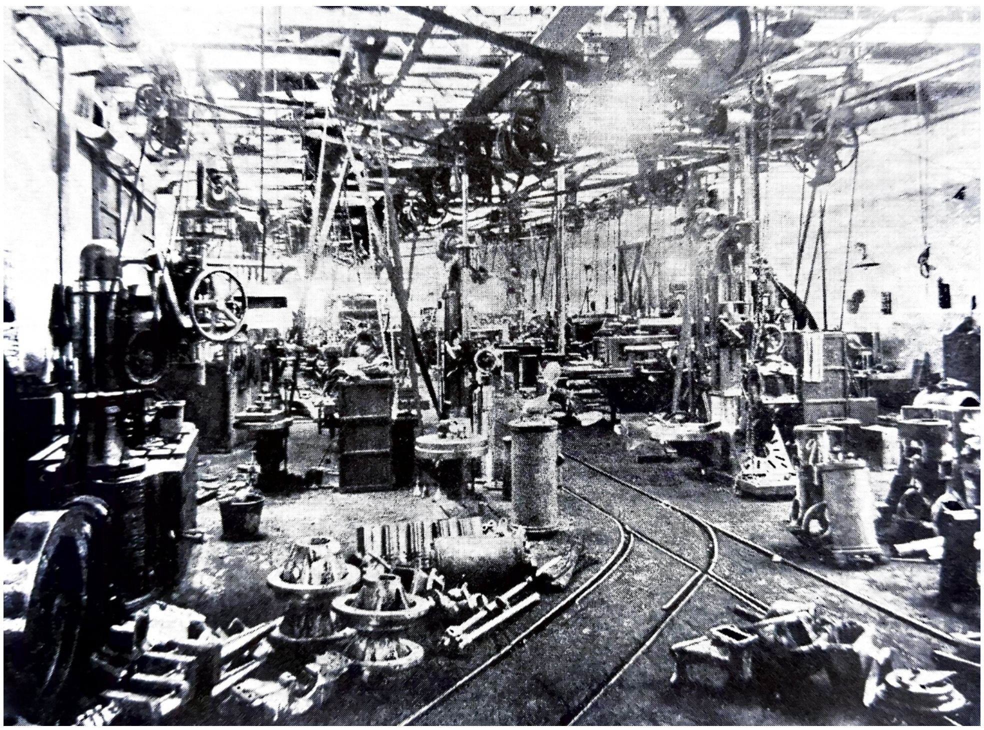
Notes: This figure shows the source of power generation in early 20th-century Japan as a five-year moving average.
Source: Ministry of Communications (1938)

Figure A2: Power Source Transition from Steam Engine to Electric Motor



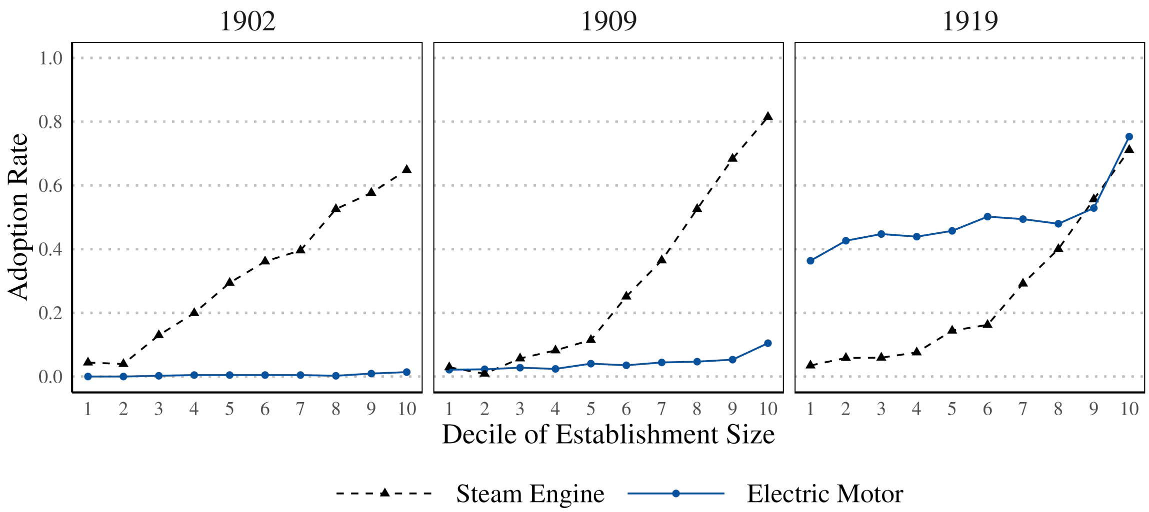
Notes: This figure displays the trends in the share of horsepower generated by each power source in Japan from 1900 to 1940 as a five-year moving average. The data comes from Minami (1979), which compiled and calculated the amount of horsepower from various statistical records published by the central government.
Source: Minami (1979)

Figure A3: Inronworks Factory Powered by Steam Engine (*Group Drive System*)

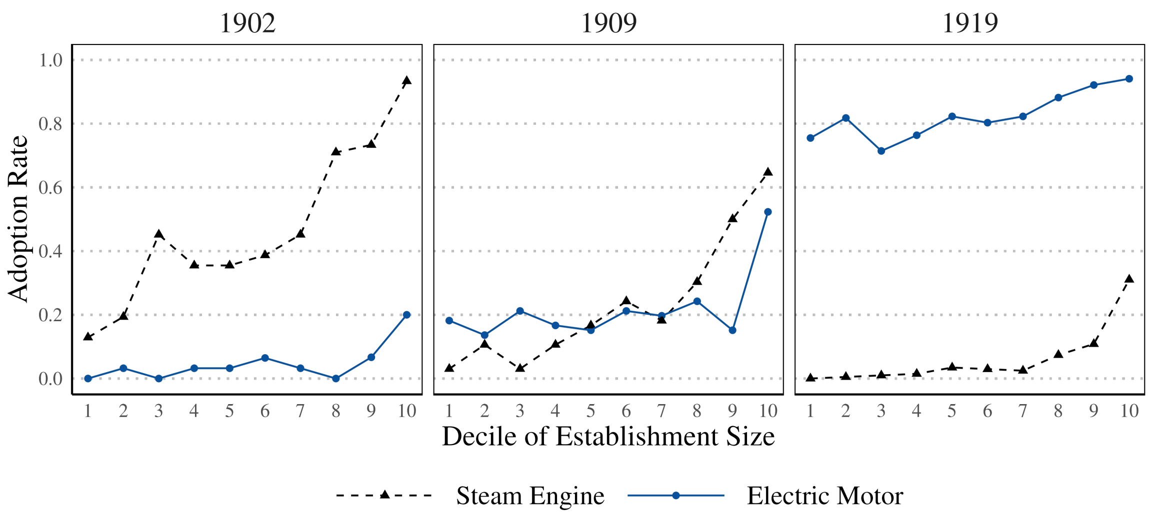


Notes: The picture shows an ironworks factory powered by steam engines in 1907, where power generated by steam engines is transmitted via shafts and belts affixed to the roof (*Group Drive System*). This production system required sizable and sturdy workshops.
Source: Ikegai Ironworks (1941)

Figure A4: Technology Adoption by Establishment Size (by Industry)



(a) Textile Industry

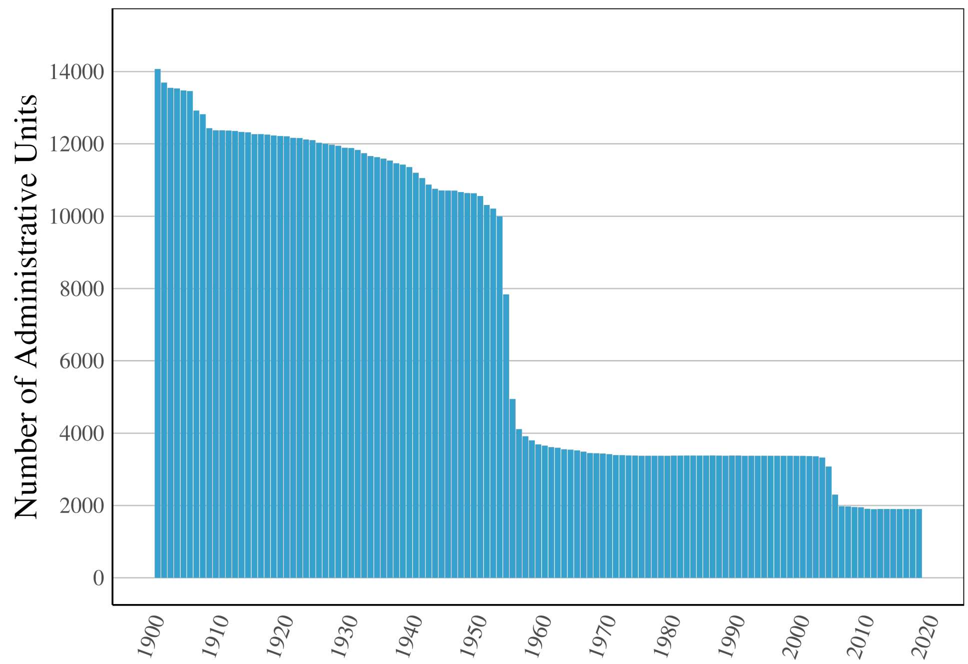


(b) Machinery Industry

Notes: These figures display the adoption rate of steam engines and electric motors by establishment size in 1902 (left), 1909 (center), and 1919 (right), where we define the number of workers as a measure of establishment size. Each point represents the average adoption rate among establishments in each decile bin. Note that the minimum number of workers is ten.
Source: Ministry of Agriculture and Commerce (1904, 1911, 1921)

Appendix B Data: Additional Details

Figure A5: Administrative Changes in Japan



Notes: This figure shows the trend in the number of administrative units in Japan from 1900 to 2020. In all analyses throughout this paper, I use the harmonized municipality unit, which represents the most aggregated unit from 1900 to 1940. For a validity check, I also harmonized the municipality transitions from 1940 to 2020, although this was not used in the main analysis.
Source: Higashide (2024)

Figure A6: Original Sample Page of the Handbook of Electric Utility Industry

34. 供給區域

地方	事業者	供給區域	從業者	備考
三重	馬野川水電株式會社	〔三重縣〕 阿山郡 阿波村. 布引村. 山田村	社長 馬岡次郎 主任技術者 田原富次 從業者 21	
三重	十社電氣株式會社	〔三重縣〕 員辨郡 十社村. 中里村. 白瀬村. 西藤原村	社長 川瀬淺之助 主任技術者 赤塚忠一 從業者 24	
岐阜 愛知	矢作水力株式會社	〔岐阜縣〕 惠那郡 大井町. 長島町. 岩村町. 本郷村 上村. 下原田村. 坂本村 〔愛知縣〕 北設樂郡 稲橋村. 武節村 額田郡 龍ヶ谷村 (電力) 〔愛知縣〕 名古屋市 岡崎市 額田郡 岡崎村. 龍ヶ谷村 碧海郡 矢作町 寶飯郡 三谷町. 蒲郡町. 塩津村 幡豆郡 西尾町	取締役 社長 福澤駒吉 副社長 杉山榮 川崎友之助 下出義雄 寒川恒貞 久留島通彦 小山柳一 監査役 岸義男 島田剛太郎 田中福之助 相談役 福澤桃介 主任技術者 小山柳一 從業者 294	9年3月岩村電氣軌道合併

Notes: This picture shows a sample page from Ministry of Communications (1930), providing information on the electricity supply areas for each utility company. I digitized this table across several editions to construct a panel dataset of electricity access status for the years 1909, 1914, 1919, 1924, and 1929.
Source: Ministry of Communications (1930)

Appendix C Descriptive Statistics

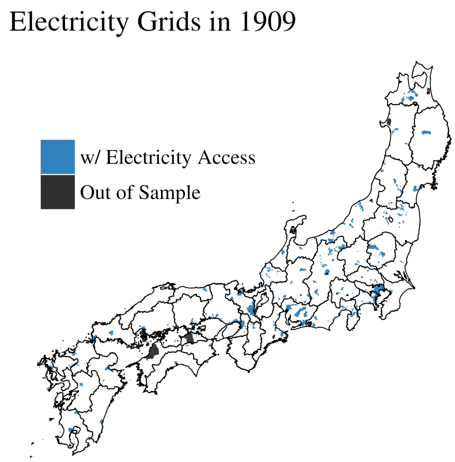
Appendix C.1 *Summary Statistics*

Table A1: Descriptive Statistics

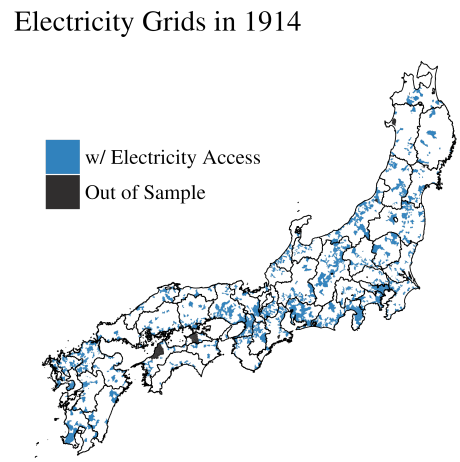
Variable	Observation	Mean	SD	Min	Max
Geography					
Area Size (km^2)	10429	27.199	40	0.105	699
Distance to Coast (km)	10429	25.111	24.8	0.01	113
Distance to the Metropolis (km)	10429	192.256	156.7	0	655
Hydropower Potential	10429	0.003	1	-0.471	11
Ruggedness (degree)	10429	10.082	7.9	0.007	35
Streamflow	10429	0.004	1	-0.844	8
Pre-Access Economic Development					
Population in 1908	10429	4631.128	15718.5	42	625193
Railway Access in 1909 (km)	10429	13.337	15.2	0.014	106
Electricity Access					
Electricity Access in 1909	10429	0.041	0.2	0	1
Electricity Access in 1914	10429	0.26	0.4	0	1
Electricity Access in 1919	10429	0.714	0.5	0	1
Electricity Access in 1924	10429	0.935	0.2	0	1
Electricity Access in 1929	10429	0.987	0.1	0	1
Manufacturing Activities in 1909					
Number of Establishments	10429	1.327	9.5	0	432
- w/ Water Wheel	10429	0.125	0.8	0	35
- w/ Steam Engine	10429	0.321	2.1	0	91
- w/ Electric Motor	10429	0.085	1.4	0	65
Number of Workers	10429	60.623	557.5	0	30121
Today's Economic Activity					
Number of Firms	10429	113.257	618.8	0	31084
Employment ($\times 10^3$)	10429	0.982	7.9	0	301
Sales ($\times 10^6$ yen)	10429	1.533	28.6	0	2151

Notes: This table shows the summary statistics of the municipality characteristics. The Metropolis refers to Tokyo, Yokohama, Nagoya, Kyoto, Osaka, and Kobe, stipulated as the six largest cities by the law in 1922. "Streamflow" indicates the estimated mean annual streamflow weighted by the area size and "Ruggedness" is the average slope of the municipality. Note that "Hydropower Potential" and "Streamflow" are standardized so that the mean is zero and the standard deviation is one. Railway Access means the minimum distance to the nearest railway station.

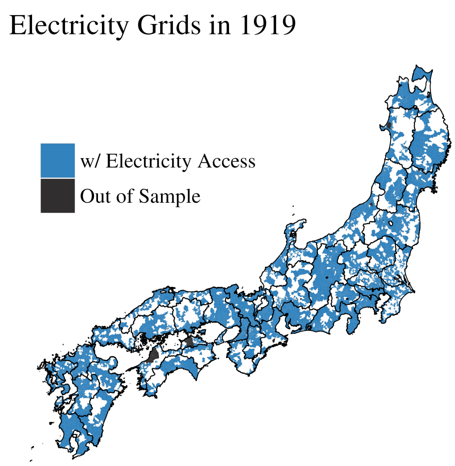
Figure A7: Expansion of Electricity Grids in Japan



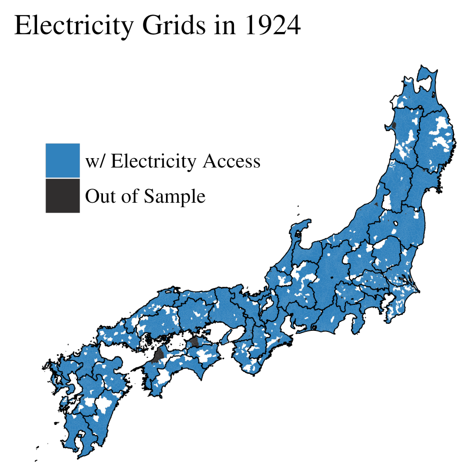
(a) 1909



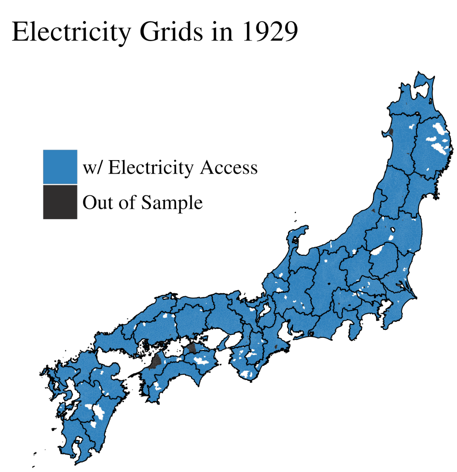
(b) 1914



(c) 1916



(d) 1919



(e) 1924

Appendix D Additional Results

Appendix D.1 *IV: Hydropower potential*

Table A2: Hydropower Potential and Manufacturing Activities

	Number of Establishments					
	Total			w/ Water Wheel		
	(1)	(2)	(3)	(4)	(5)	(6)
Hydropower Potential × 1902	-0.024	-0.020	-0.004	-0.017	-0.016	-0.010
	(0.022)	(0.023)	(0.023)	(0.020)	(0.020)	(0.021)
Hydropower Potential × 1916	0.015	0.023	0.018	-0.001	-0.002	-0.003
	(0.016)	(0.016)	(0.017)	(0.010)	(0.010)	(0.011)
Hydropower Potential × 1919	0.091**	0.090**	0.080**	0.000	0.001	0.000
	(0.036)	(0.037)	(0.038)	(0.021)	(0.021)	(0.021)
Municipality FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Geography × Year FE	✓	✓	✓	✓	✓	✓
Pop. density 1908 × Year FE	✓	✓	✓	✓	✓	✓
Streamflow × Year FE		✓	✓		✓	✓
Ruggedness × Year FE			✓			✓
Observations	40,020	40,020	40,020	40,020	40,020	40,020
Adjusted R^2	0.68	0.68	0.68	0.58	0.58	0.58
Mean of dep.var	0.72	0.72	0.72	0.09	0.09	0.09

Notes: Observations are municipalities where the electricity supply began after 1909. Robust standard errors clustered at the municipality level are reported in parentheses. The dependent variable "w/ Water Wheel" and "w/ Steam Engine" represent the number of establishments using water wheels and the number of establishments using steam engines, respectively. The independent variable, "Hydropower Potential", is a standardized measure of municipality-level potential for hydropower generation, with standard deviation of one, thus the estimates reflect differences in economic activities with one standard deviation higher hydropower potential. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A3: First Stage: Relationship between Hydropower Potential and Electricity Access

	Electricity Access in 1914			Early Electricity Access		
	(1)	(2)	(3)	(4)	(5)	(6)
Hydropower Potential	0.041***	0.042***	0.041***	0.216***	0.219***	0.250***
	(0.007)	(0.007)	(0.007)	(0.074)	(0.076)	(0.076)
Prefecture FE	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓
Streamflow		✓	✓		✓	✓
Ruggedness			✓			✓
Observations	10,005	10,005	10,005	10,005	10,005	10,005
Adjusted R^2	0.23	0.23	0.23	0.31	0.31	0.31
F-test (1st stage)	72.7	70.1	65.9	18.0	17.9	22.7
Mean of dep.var	0.23	0.23	0.23	15.7	15.7	15.7

Notes: First stage estimates are reported. Observations are municipalities where the electricity supply began after 1909. Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. The instrumental variable, "Hydropower Potential", is a standardized measure of municipality-level potential for hydropower generation, with standard deviation of one, thus the estimates reflect differences in electricity access with one standard deviation higher hydropower potential. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Appendix D.2 *Short-run effect: Robustness*

Table A4: Robustness: Effect of Electricity Access on Industrialization

	Δ Number of Establishments (1909-1919)				Demographics	
	Total	w/ Electric Motor	Total	w/ Electric Motor	Δ Mnf. Workers (1909-1919)	Δ Pop. (1908-1918)
	(1)	(2)	(3)	(4)	(5)	(6)
Electricity Access in 1914	0.298***	0.551***	2.02*	1.29***	122.5***	156.0
	(0.088)	(0.062)	(1.04)	(0.409)	(44.7)	(376.8)
Δ Railway Access	-0.038	-0.034	0.036	-0.002	2.19	-28.4
	(0.044)	(0.026)	(0.070)	(0.032)	(3.13)	(28.1)
Model	OLS	OLS	IV	IV	IV	IV
Prefecture FE	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓	✓
Observations	10,005	10,005	10,005	10,005	10,005	9,991
First stage F-stat			64.6	64.6	64.6	65.5
Mean of dep.var	0.30	0.36	0.30	0.36	24.7	228.1

Notes: Second stage estimates are reported. Observations are municipalities where the electricity supply began after 1909. Estimates are from instrumental variables specifications in which the endogenous variable is "Electricity Access in 1914" and the instrument is the "Hydropower Potential". Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). The variable "Δ Railway Access" represents the change in the distance to the nearest railway station between 1909 and 1919. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A5: Robustness: Drop Municipalities with Large Hydropower Stations

	Δ Number of Establishments (1909-1919)				Demographics	
	Total	w/ Electric Motor	Total	w/ Electric Motor	Δ Mnf. Workers (1909-1919)	Δ Pop. (1908-1918)
	(1)	(2)	(3)	(4)	(5)	(6)
Electricity Access in 1914	0.328***	0.560***	1.34*	1.32***	90.0**	121.1
	(0.090)	(0.064)	(0.771)	(0.395)	(40.8)	(357.6)
Model	OLS	OLS	IV	IV	IV	IV
Prefecture FE	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓	✓
Observations	9,864	9,864	9,864	9,864	9,864	9,850
First stage F-stat			67.4	67.4	67.4	68.3
Mean of dep.var	0.30	0.37	0.30	0.37	24.5	224.3

Notes: Second stage estimates are reported. Observations are municipalities where the electricity supply began after 1909. Estimates are from instrumental variables specifications in which the endogenous variable is "Electricity Access in 1914" and the instrument is the "Hydropower Potential". Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

Table A6: Falsification: Effect of Electricity Access on Entrant Activities (1902-1909)

	Number of Establishments						Demographics	
	Total		w/ Steam Engine		w/ Electric Motor		Mnf. Workers	
	(1) Δ All	(2) Entrant	(3) Δ All	(4) Entrant	(5) Δ All	(6) Entrant	(7) Δ All	(8) Entrant
Electricity Access in 1914	0.176	0.762*	0.383**	0.181	0.012	0.011	24.4	32.8**
	(0.693)	(0.406)	(0.170)	(0.127)	(0.016)	(0.009)	(28.0)	(14.5)
Model	IV	IV	IV	IV	IV	IV	IV	IV
Prefecture FE	✓	✓	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓	✓	✓	✓
Observations	10,005	10,005	10,005	10,005	10,005	10,005	10,005	10,005
First stage F-stat	65.9	65.9	65.9	65.9	65.9	65.9	65.9	65.9
Mean of dep.var	0.33	0.33	0.07	0.10	0.004	0.002	10.5	11.7

Notes: Second stage estimates are reported. Observations are municipalities where the electricity supply began after 1909. Estimates are from instrumental variables specifications in which the endogenous variable is "Electricity Access in 1914" and the instrument is the "Hydropower Potential". Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. The vector of control variables, "Geography", includes the municipality area size (in log), the distance to the coast (in log), and the distance to the metropolis (in log). *, **, and *** indicate significance at the 10%, 5%, and 1% levels.