Connecting to Electricity: Technical Change and Regional Development

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Motivation: How did electrification stimulate manufacturing?

- Manufacturing growth at the dawn of the 20th Century.
  - The Second Industrial Revolution.

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- **From Steam Engine to Electric Motor:**
  - A groundbreaking shift in general purpose technology (Bresnahan and Trajtenberg, 1995).
  - Rapid diffusion and replacement, e.g., $\approx$ 30 years in Japan.
  - The spatial structure of the technological shock can have persistent impacts.

This project: Popularization of powered factory

- Electric motors lower barriers to entry in the mfg. sector with powered factory.
  - Substantial reduction in ***fixed costs*** of technology adoption (Minami, 1979).
  - Small or middle-sized establishments can enter the market w/ powered factory.
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  - **Newly digitized official records** of establishment-level data and electricity access.
  - **Empirical strategy** exploiting geographical suitability of hydropower generation.

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- Explore this hypothesis in early 20th-century Japan by combining:
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- **Key findings**:
  1. Electricity access increased # establishments and manufacturing workers.
  2. New entrants accounted for over 90% of this manufacturing growth (w.r.t. workers).
  3. Regions with earlier electricity access experienced larger population growth.

Related literature

1. **Historical impact of electrification**:
   - Structural transformation in Norway and the U.S. (Leknes and Modalsli, 2020 Gaggl et al., 2021).
   - *Scale-biased tech change* is associated with wealth inequality (Reichardt, 2024).
   - Kitchens and Fishback (2015), Lewis (2018), Lewis and Severnini (2020), Molinder et al. (2021), Kawaguchi et al. (2024).

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2. **Evolution of the geography of economic activities**:
   - Role of history (e.g., Davis and Weinstein, 2002, Bleakley and Lin, 2012, Kline and Moretti, 2014, Hanlon, 2017).
   - Technological shocks: printing press (Dittmar, 2011), steam engine (Yamasaki, 2023, Hornbeck et al., 2024).

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3. **Industrialization in Japan**:
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- *In this paper*, ***technical change from steam engines to electric motors***:
  - First empirical evidence that ***new entrants*** drove this tech change and manufacturing growth.
  - The persistent impacts of the timing of electrification.

Outline of Talk

Introduction

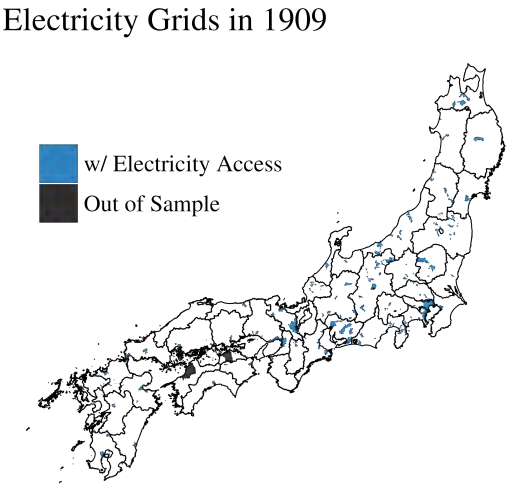
Historical Background

Data & Empirical Strategy

Results

Historical Background: A tale of electrification

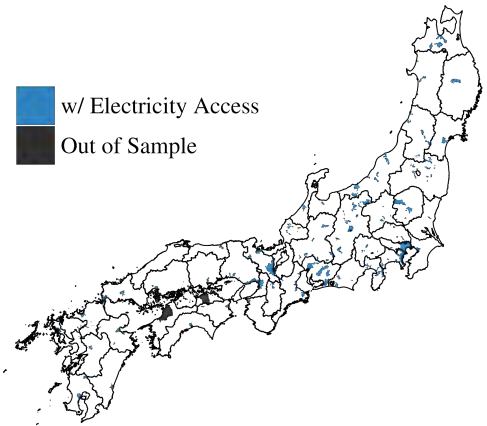
Expansion of electricity grids (1909–1914)



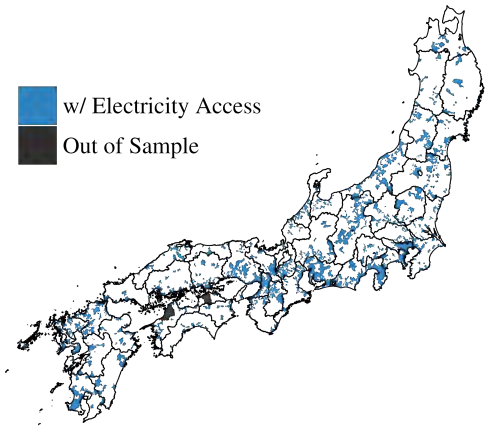
- **1880s: Start of electricity supply**
  - For lighting purposes
  - Thermal power in urban areas
  - By private firms
  - Limited grid expansion
- **1900s: Rapid grid expansion**
  - Long-distance transmission
  - Cheap hydroelectric power
  - Rising demand from mfg. sectors

Expansion of electricity grids (1909–1914)

Electricity Grids in 1909

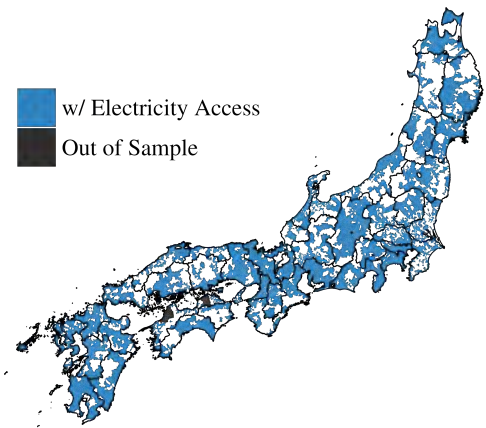


Electricity Grids in 1914



Expansion of electricity grids (1919–1924)

Electricity Grids in 1919



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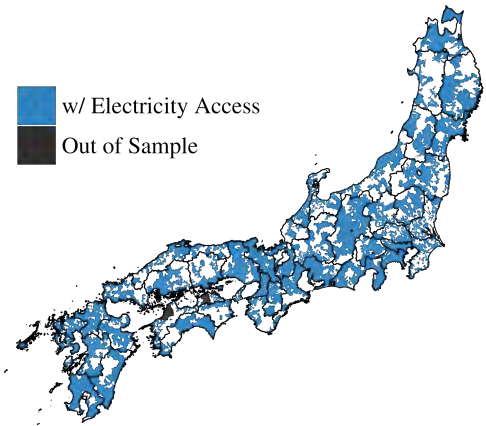
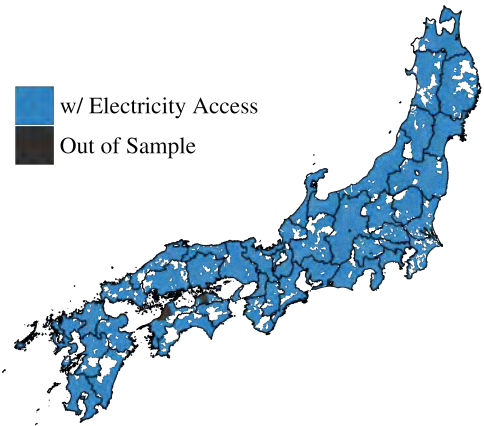
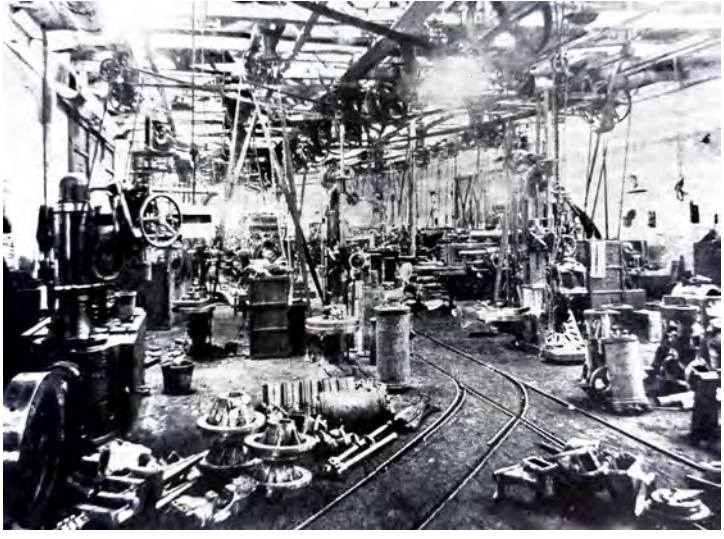


Electricity Grids in 1924



▸ Power Generation ▸ Horsepower Transition

High fixed cost of steam engine (*Group drive system*)



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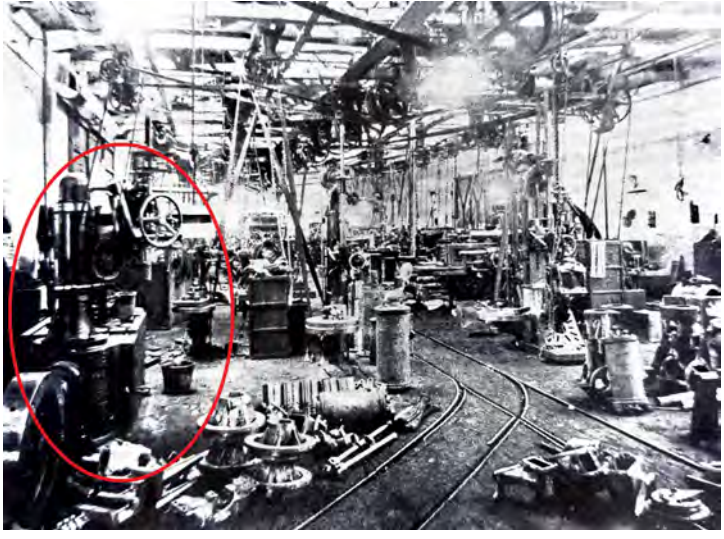

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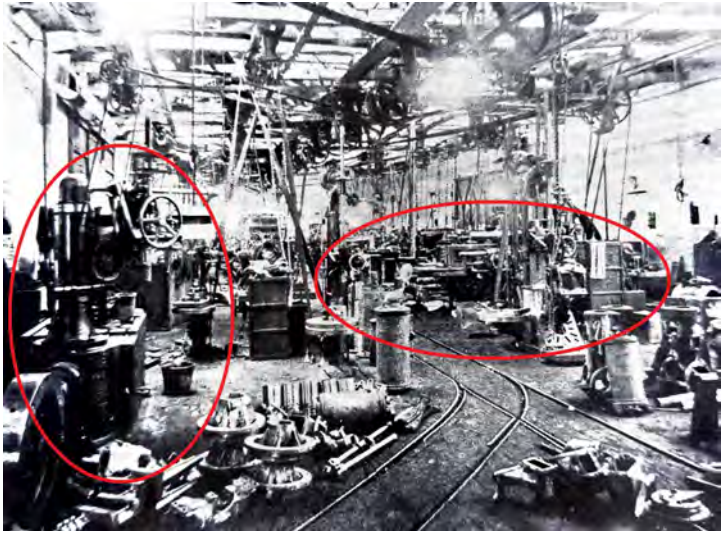

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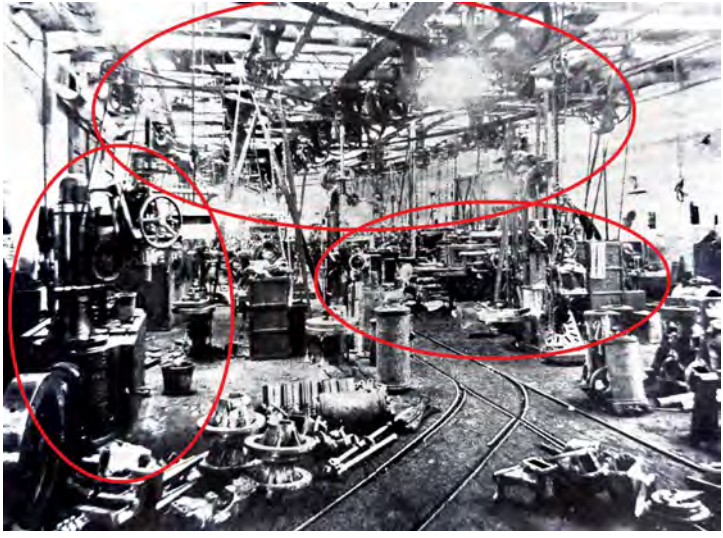
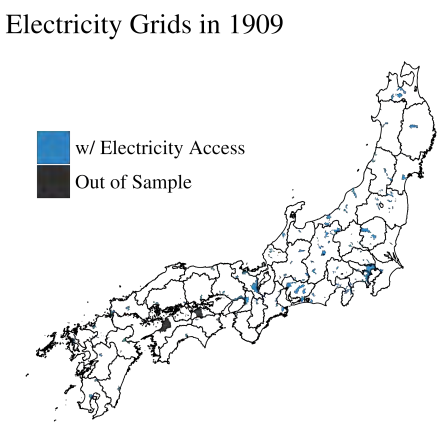
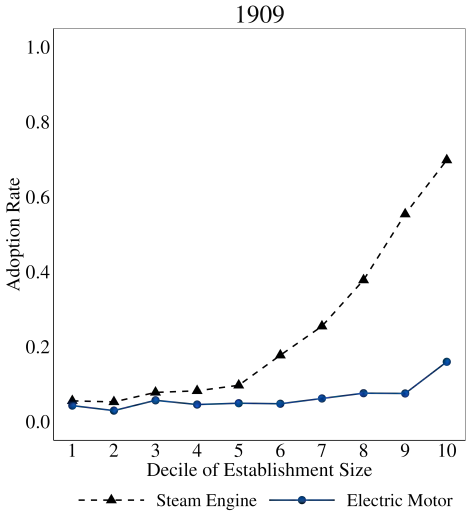


Popularization of powered factory





▸ All ▸ Textile ▸ Chemicals ▸ Machinery ▸ Metal ▸ Food

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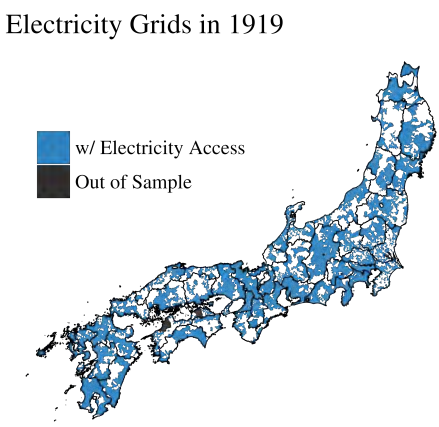

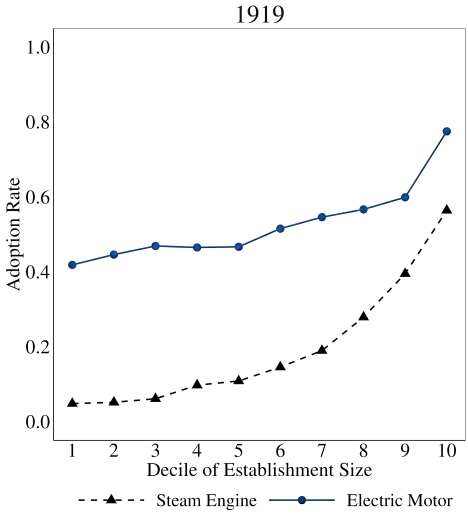

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Data & Empirical Strategy

Data: Newly digitized official records

1. **Handbook of Factory** (*Kojo Tsuran*):
   - All est. with 10+ workers (1902, 1909, 1916, 1919).
   - # male/female workers, HP by power source, industry, funding year, and address.
   - # establishments: 11,914 in 1909, 23,004 in 1919.

▸ N Est. by Industry ▸ Workers by Industry

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2. **Handbook of Electric Utility Industry** (*Denki Jigo Yoran*):
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3. **Population census in early 20th-century.**
   - 1908, 1913, 1918, 1920, 1925, 1930, and 1935.

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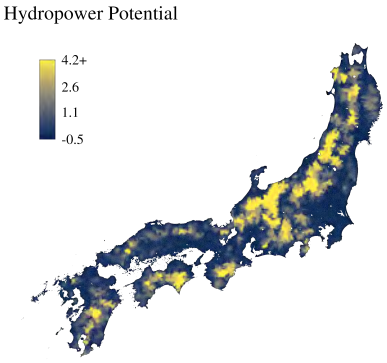
IV: Hydropower potential

$$\text{Hydropower Potential}_j = \underbrace{\text{Water Volume Index}_j}_{\text{Estimates from Arai et al. (2022)}} \times \text{Hydraulic Head Height}_j.$$



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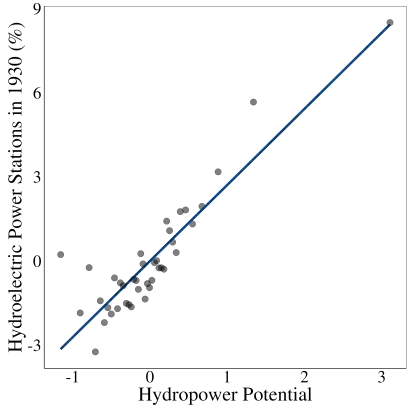
  - F-stat = 57.7 (btwn. the access in 1914).



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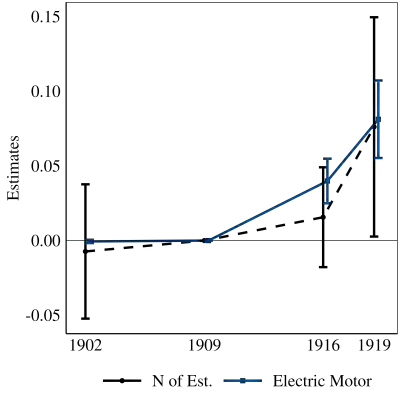
- **Exclusion restriction**:
  - Check the reduced form relationship.
  - No correlation before the grid expansion.
  - But, strong impacts after the expansion.



▸ Hydropower Potential ▸ Relevance ▸ Exclusion (Eq.) ▸ Exclusion (Result)

Results: How did electrification stimulate manufacturing?

Main Specification

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

- i: municipality without electricity supply in 1909, p: prefecture.
- ΔY_{ip}: Change in outcomes from 1909 to 1919.
- $\text{Electricity Access}_{i,1914}$: Electricity accessibility in municipality i in 1914.
- $\ln(\text{PopDens}_{i,1908})$: Log of population density in 1908.
- Geography_i: Area size, dist. to the coast, and dist. metropolis.
- τ_p: prefecture fixed effects.

▸ First stage

2nd stage: Effect of electricity access on industrialization

	Δ Establishments				Δ Mnf. Workers	
	All	w/ Electric Motor	All	w/ Electric Motor	All	
	(1)	(2)	(3)	(4)	(5)	(6)
Electricity Access in 1914	0.323***	0.570***	2.04*	1.37***	39.8***	123.2***
	(0.095)	(0.066)	(1.06)	(0.432)	(7.77)	(44.1)
Model	OLS	OLS	IV	IV	OLS	IV
Prefecture FE	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓	✓
Observations	10,098	10,098	10,098	10,098	10,098	10,098
First KP-stat			29.4	29.4		29.4
Mean of dep.var	0.30	0.37	0.30	0.37	25.2	25.2

Notes: Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

▸ Industry (N Est.) ▸ Industry (Workers)

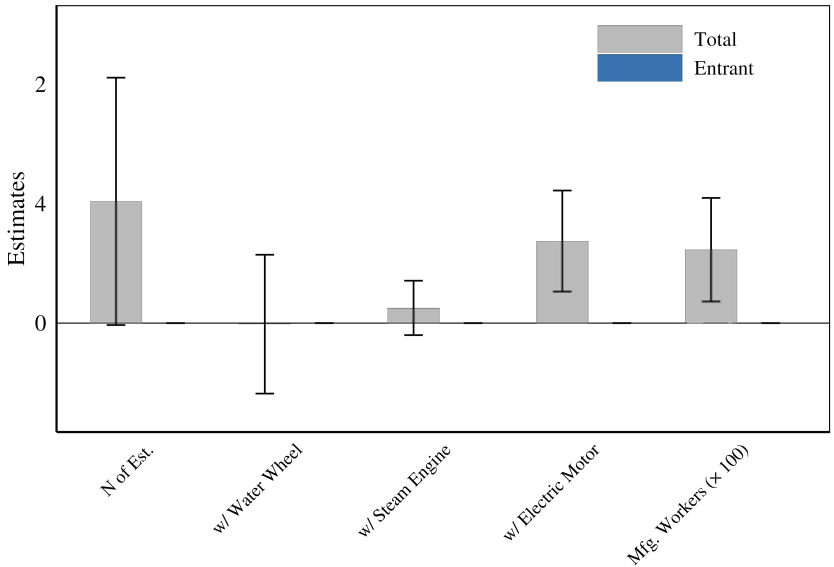
Main result: Robustness

- **Placebo test** ‣ Placebo
  - Concern about unobserved preexisting regional characteristics.
  - Replacing the outcome with the change in 1902-1909 (= before the access).
  - $\rightarrow$ Much smaller and insignificant effect.

- **Potential confounders** ‣ Confounders
  - Other factors correlated with the access could impact the manufacturing.
  - Controlling for improved railway access, power generation stations, and coal access.
  - $\rightarrow$ Nearly identical and still statistically significant.

- **Spillover effects** ‣ Spillover (Def.) ‣ Spillover
  - The electrification rate of neighboring regions may bias the estimation.
  - Controlling for the neighborhood electricity access.
  - $\rightarrow$ Nearly identical and still statistically significant.

Mechanism: Entrants as driving force



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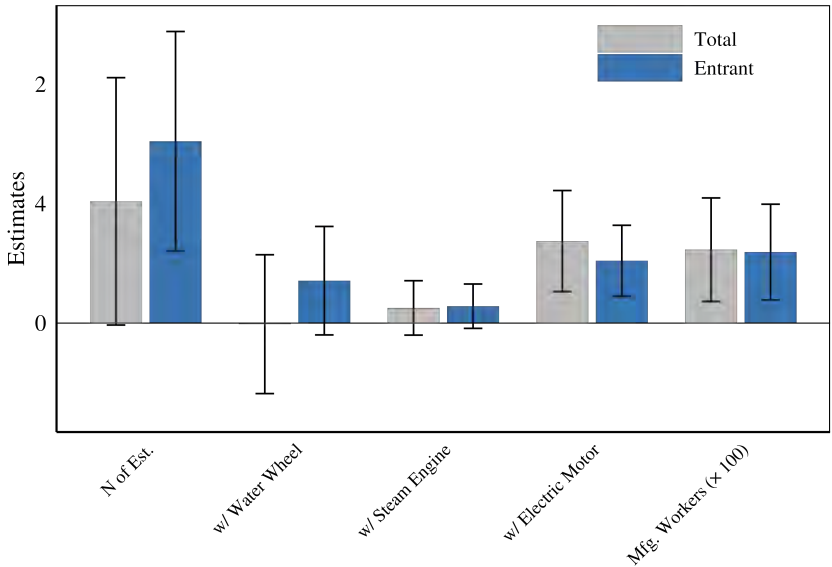
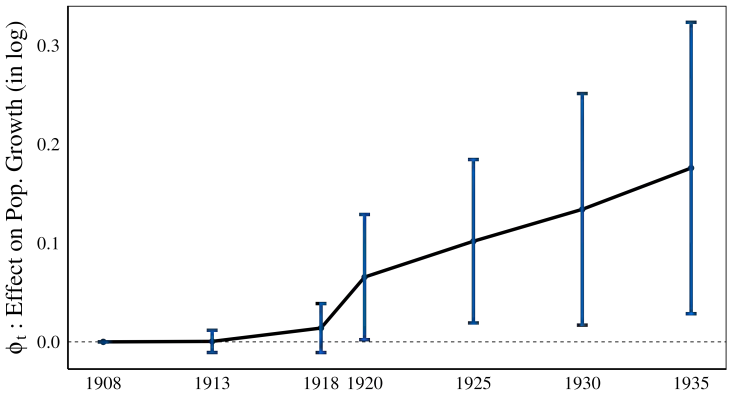


Long-run impacts: Population growth

$$\ln\left(\frac{\text{Population}_{it}}{\text{Population}_{i,1908}}\right) = \phi_t \underbrace{\text{Early Electricity Access}_i}_{\text{1929}-\text{Year of first access}} + \xi_t X_i + \varsigma_{pt} + \epsilon_{ipt},$$



Conclusion

- ***How did electrification stimulate manufacturing?***

- **Data & Empirical Strategy**:
  - Newly digitized records of electricity access and manufacturing activities.
  - IV: Geographical suitability of hydroelectric power generation.

- **Findings**:
  - Electricity access stimulated mfg. activities, in particular w/ electric motors.
  - This manufacturing growth was driven by new entrants.
  - Regions w/ earlier access experienced higher population growth.

- **Next steps**:
  - Markup changes depending on the establishment size.
  - Detailed mechanisms behind the persistent effects.

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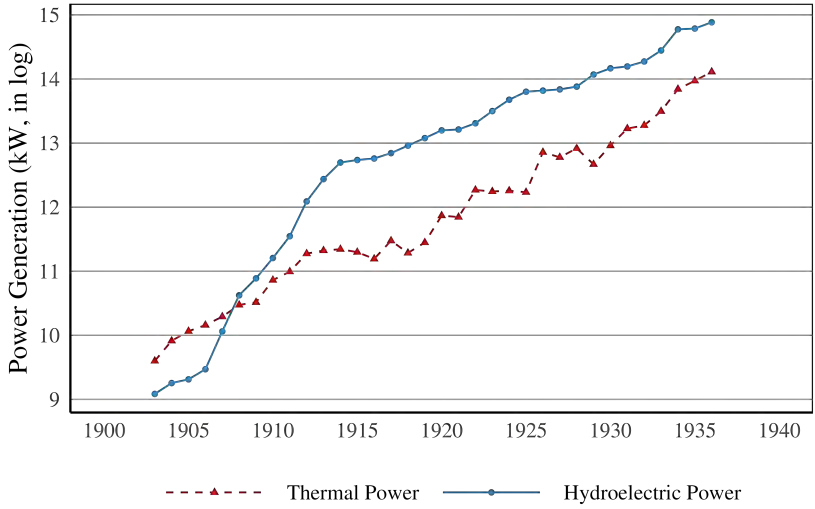
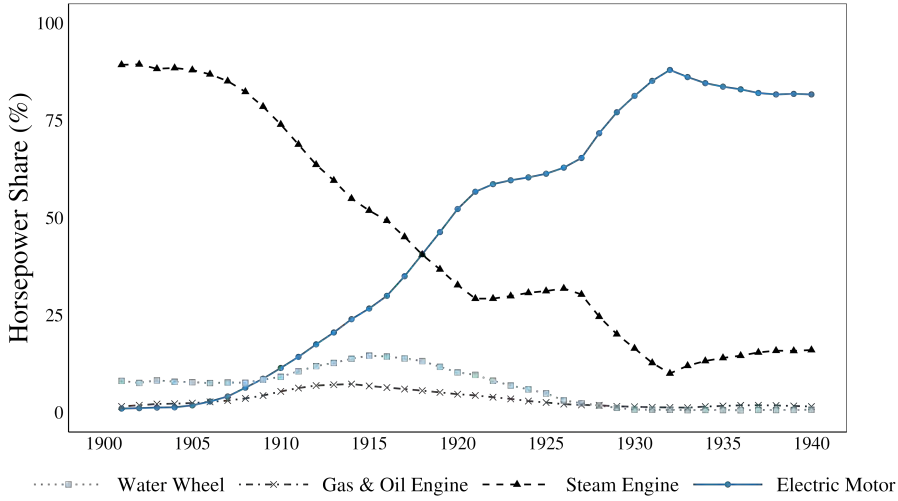
Source of power generation



Back

From steam engine to electric motor



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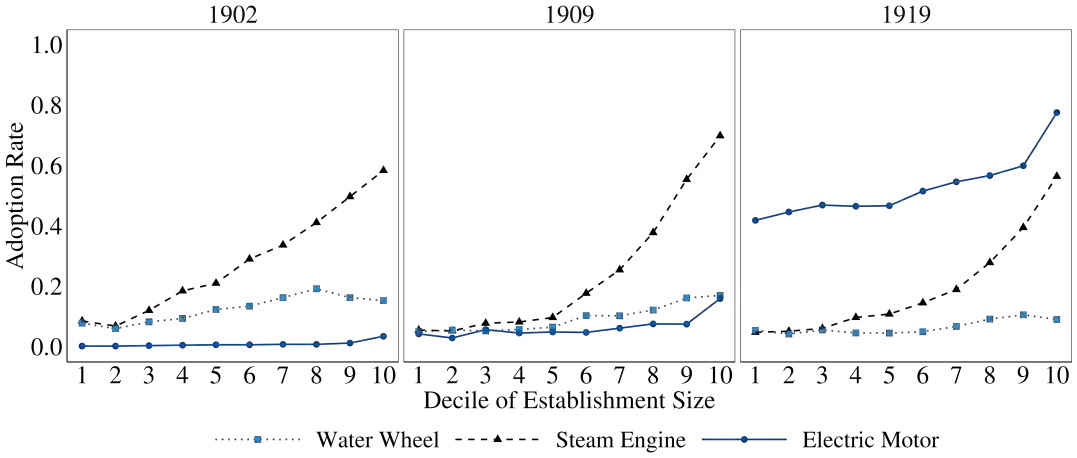
Technology adoption



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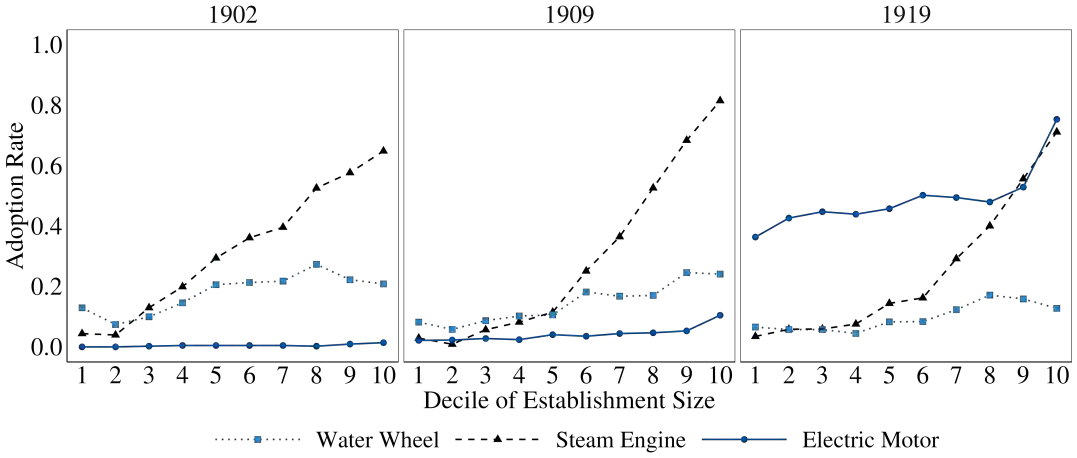
Technology adoption: Textile



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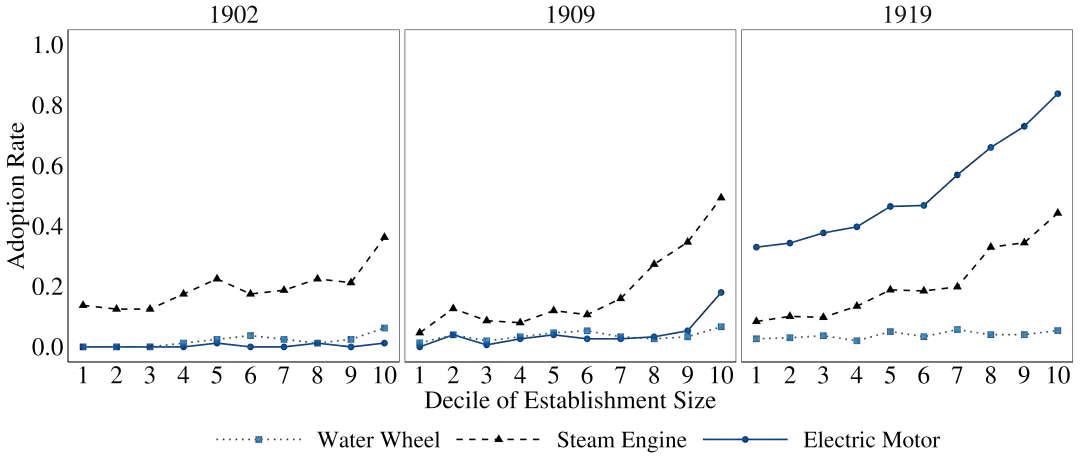
Technology adoption: Chemicals



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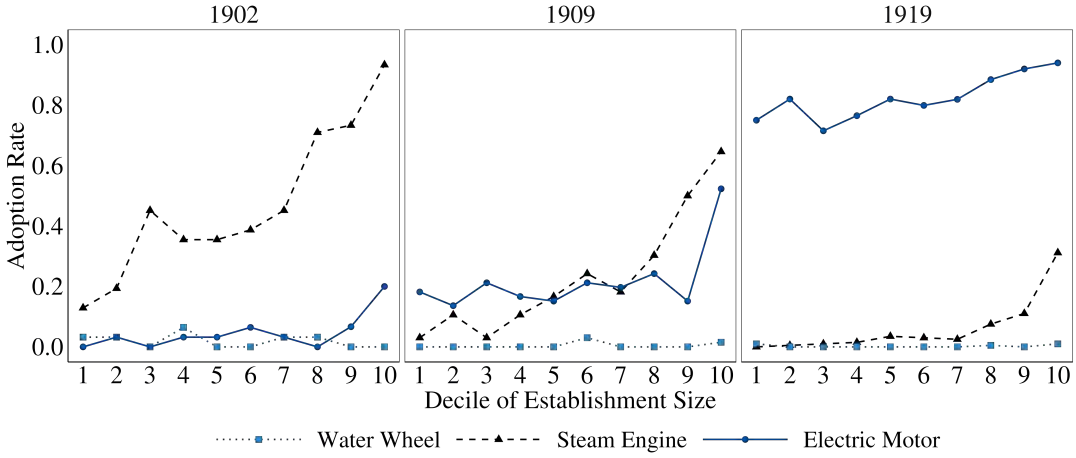
Technology adoption: Machinery



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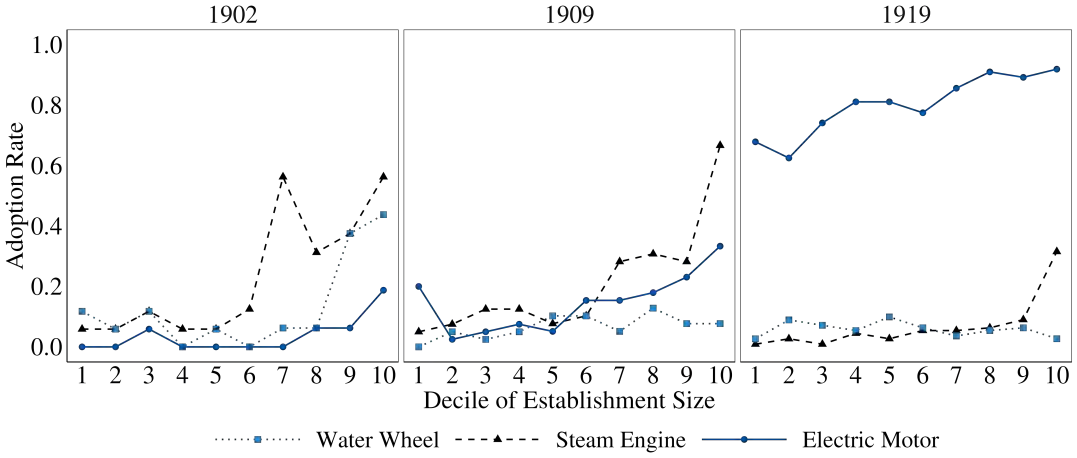
Technology adoption: Metal



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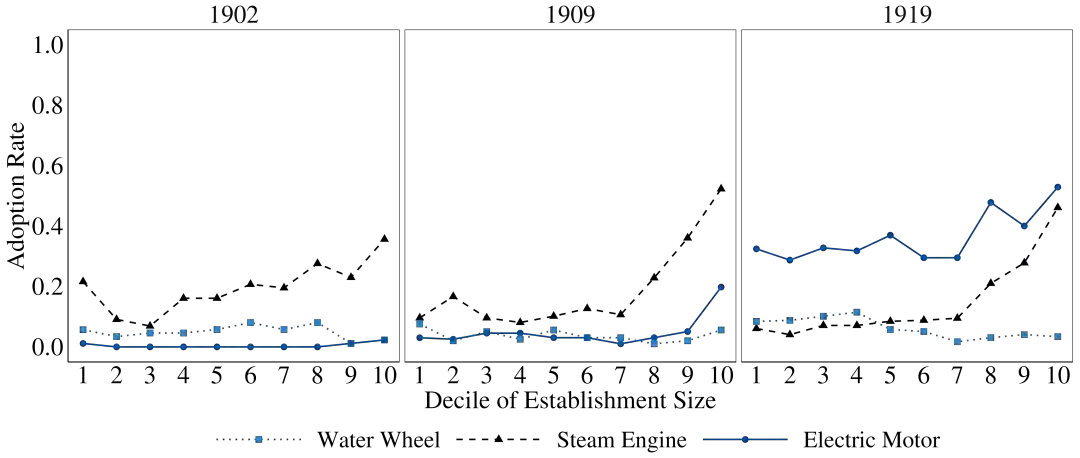
Technology adoption: Food



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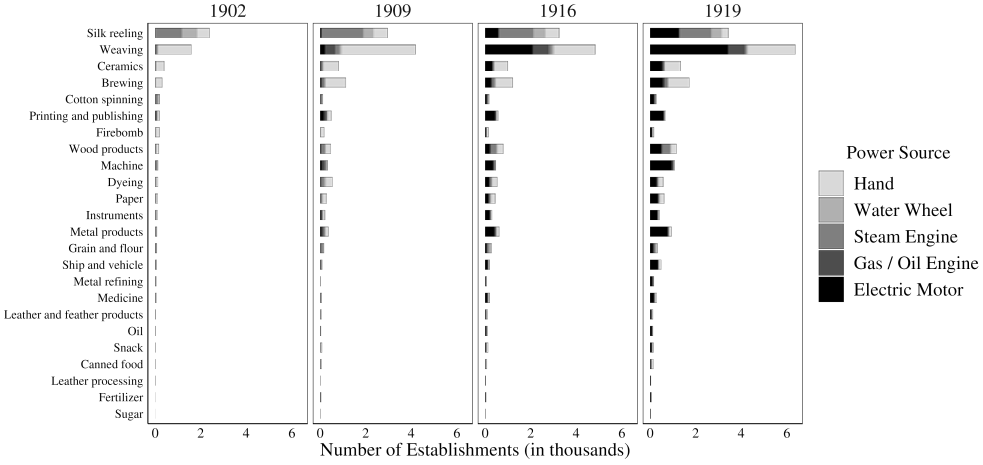
Number of establishments by industry



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Number of workers by industry

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IV: Hydropower potential

- Theoretical hydropower potential of hydropower generation in basin j: (Arai et al., 2022)

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

  - Power generation depends on streamflow and hydraulic head (Basso and Botter, 2012).
  - Water Volume Index$_j$: Cumulative annual flow volume of basin j.
  - Hydraulic Head Height$_j$: Elevation difference between the basin and areas within a 1km.

- Arai et al. (2022) estimates the W_i for small-sized basins ($\approx 10 km^2$) in Japan with
  - 176 basin geographical characteristics.
  - 389 basins with discharge records (ave. 17.1 years).
  - Neural network model.

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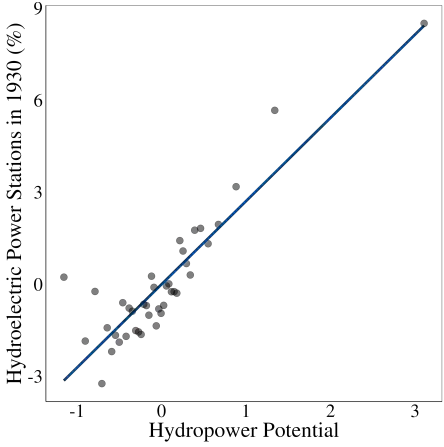
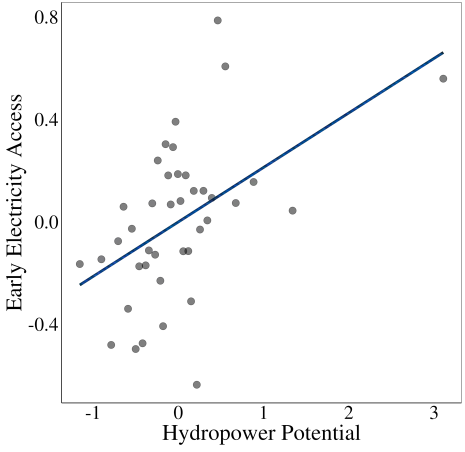
Hydropower potential and early electricity access



(a) Hydroelectric generation



(b) Early electricity access

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Hydropower potential and economic activities

$$
\begin{aligned}
Y_{it} = &\sum_{s \neq 1909} \beta_s \, \text{Hydropower Potential}_i \times \mathbf{1}\{\text{Year} = s\} + \\
&\sum_{s \neq 1909} \lambda_s \, \ln(\text{PopDens}_{i,1908}) \times \mathbf{1}\{\text{Year} = s\} + \\
&\sum_{s \neq 1909} \gamma_s \, \text{Geography}_i \times \mathbf{1}\{\text{Year} = s\} + \alpha_i + \delta_t + v_{it},
\end{aligned}
$$

- i: municipality where electricity supply began after 1909.
- $t \in \{1902, 1909, 1916, 1919\}$: year.
- Y_{it}: # establishments.
- Hydropower potential$_i$: Suitability for hydropower generation.
- Geography$_i$: Area size, dist. to the coast, and dist. metropolis.
- (α_i, δ_t): municipality and year fixed effects.

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Hydropower potential matters only after the grid expansion

	Number of Establishments					
	All			w/ Electric Motor		
	(1)	(2)	(3)	(4)	(5)	(6)
Hydropower Potential × 1902	-0.027	-0.023	-0.007	-0.001	-0.001	-0.001
	(0.022)	(0.022)	(0.023)	(0.001)	(0.001)	(0.001)
Hydropower Potential × 1916	0.013	0.021	0.016	0.047***	0.044***	0.040***
	(0.016)	(0.016)	(0.017)	(0.007)	(0.007)	(0.008)
Hydropower Potential × 1919	0.087**	0.085**	0.076**	0.101***	0.093***	0.081***
	(0.036)	(0.037)	(0.037)	(0.014)	(0.013)	(0.013)
Municipality FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Streamflow × Year FE		✓	✓		✓	✓
Ruggedness × Year FE			✓			✓
Observations	40,392	40,392	40,392	40,392	40,392	40,392
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: Robust standard errors clustered at the municipality level are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

First stage: Effect of electricity access on industrialization

	Electricity Access in 1914			Early Electricity Access		
	(1)	(2)	(3)	(4)	(5)	(6)
Hydropower Potential	0.038***	0.038***	0.038***	0.132	0.125	0.178**
	(0.007)	(0.007)	(0.007)	(0.081)	(0.083)	(0.084)
Prefecture FE	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓
Streamflow		✓	✓		✓	✓
Ruggedness			✓			✓
Observations	10,098	10,098	10,098	10,098	10,098	10,098
F-test (1st stage)	63.1	59.7	57.7	6.2	5.4	10.7
Mean of dep.var	0.23	0.23	0.23	15.5	15.5	15.5

Notes: Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

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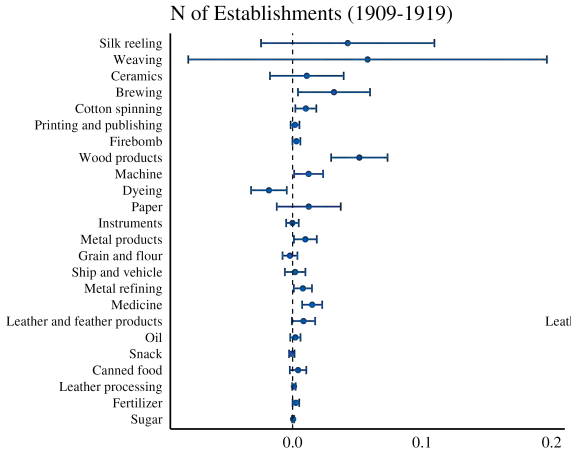
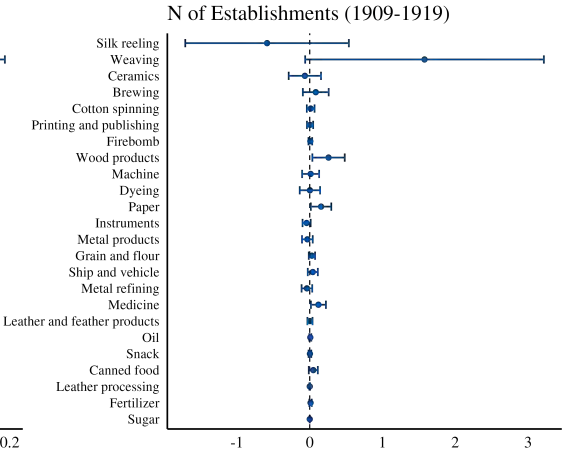
2nd stage: Industry heterogeneity



(a) OLS



(b) IV

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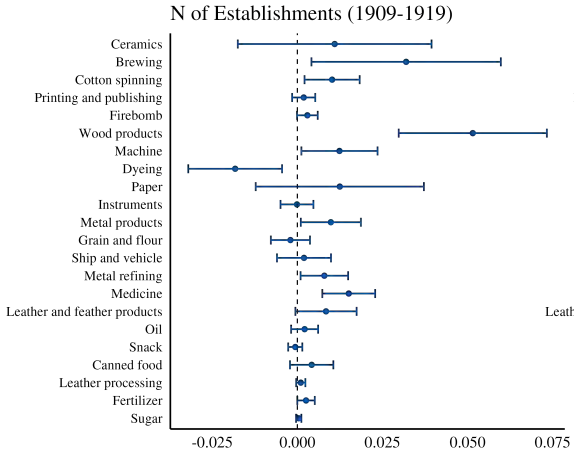
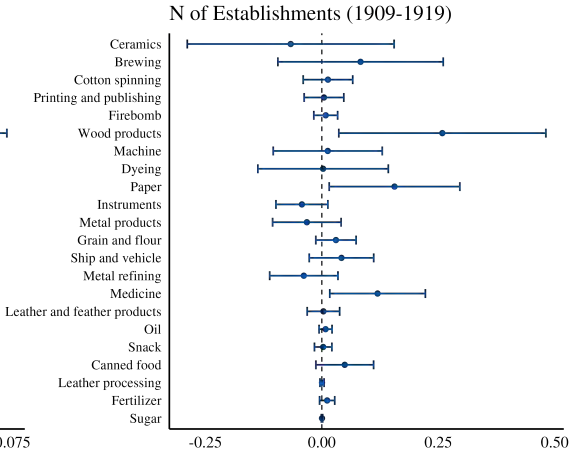
2nd stage: Industry heterogeneity



(a) OLS



(b) IV

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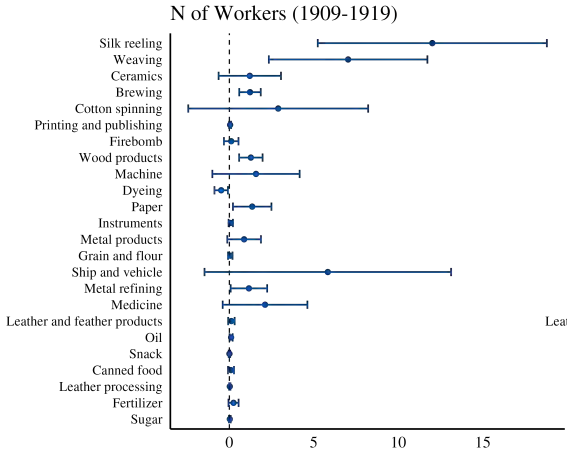
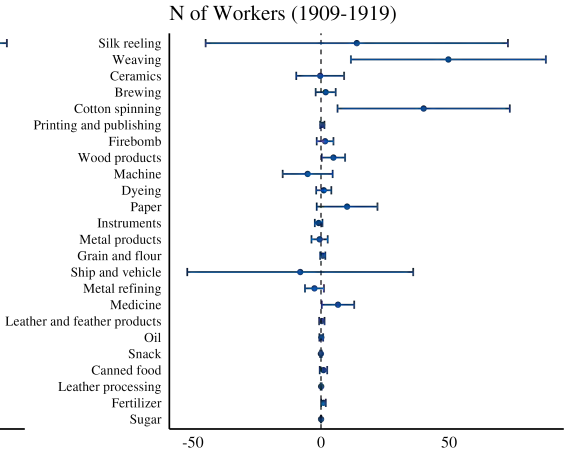
2nd stage: Industry heterogeneity



(a) OLS



(b) IV

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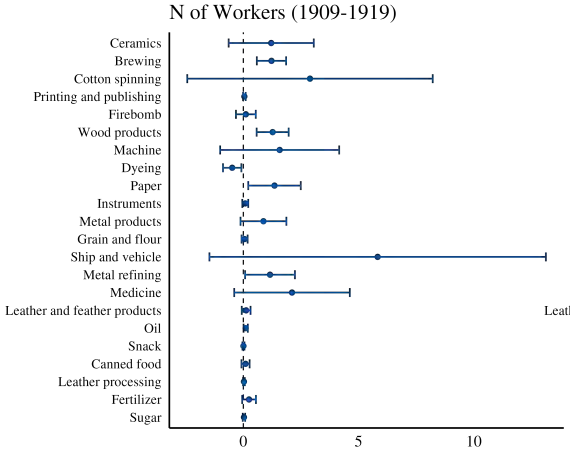
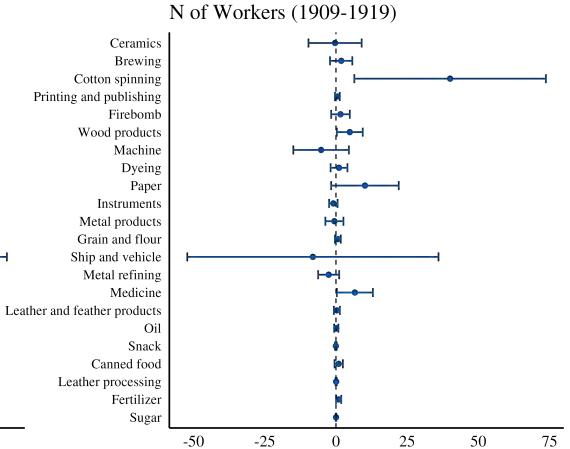
2nd stage: Industry heterogeneity



(a) OLS



(b) IV

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Robustness: Placebo test

	Δ Establishments				Δ Mnf. Workers	
	All	w/ Electric Motor	All	w/ Electric Motor	All	
	(1)	(2)	(3)	(4)	(5)	(6)
Electricity Access in 1914	0.404***	0.005**	0.249	0.013	11.2***	26.7
	(0.084)	(0.002)	(0.741)	(0.017)	(3.90)	(29.6)
Model	OLS	OLS	IV	IV	OLS	IV
Prefecture FE	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓	✓
Observations	10,098	10,098	10,098	10,098	10,098	10,098
First KP-stat			29.4	29.4		29.4
Mean of dep.var	0.33	0.004	0.33	0.004	10.5	10.5

Notes: Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.

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Robustness: Potential confounders

	Δ Establishments				Δ Labor	
	Total	w/ Electric Motor	Total	w/ Electric Motor	Male	Female
	(1)	(2)	(3)	(4)	(5)	(6)
Electricity Access in 1914	0.326***	0.574***	2.06**	1.38***	21.8	91.2***
	(0.093)	(0.066)	(1.05)	(0.437)	(27.9)	(31.3)
Δ Railway Access	0.043	0.018	0.035	0.014	-0.565	1.28
	(0.036)	(0.018)	(0.038)	(0.018)	(1.21)	(1.60)
Hydropower Station	-0.152*	-0.117***	-0.191**	-0.135***	-0.920	-1.15
	(0.082)	(0.040)	(0.088)	(0.044)	(2.11)	(4.53)
Thermalpower Station	0.333	0.377**	0.365	0.392**	17.7	9.95
	(0.237)	(0.179)	(0.231)	(0.177)	(16.7)	(11.2)
Coal Access	-0.015	0.020	-0.021	0.017	-5.91*	-2.14
	(0.055)	(0.040)	(0.052)	(0.037)	(3.53)	(2.12)
Model	OLS	OLS	IV	IV	IV	IV
Prefecture FE	✓	✓	✓	✓	✓	✓
Observations	10,098	10,098	10,098	10,098	10,098	10,098
First KP F-stat			29.8	29.8	29.8	29.8
Mean of dep.var	0.30	0.37	0.30	0.37	10.3	15.0

Notes: This table presents the effects of electricity access in 1914 on manufacturing activities and technology adoption, estimated using

Robustness: Spillover effects (Definition)

The electrification rate of neighboring regions is defined as

$$\begin{aligned}\text{Neighborhood Access}_i &:= \sum_{j \in N(i)} \omega_{ij} \, \text{Electricity Access}_{j,1914} \\ &= \sum_{j \in N(i)} \frac{\text{Pop}_{j,08}}{\sum_{k \in N(i)} \text{Pop}_{k,08}} \, \text{Electricity Access}_{j,1914},\end{aligned}$$

where $N(i)$ is the set of neighboring municipalities of i.

- ω_{ij}: Weight of the neighboring municipality j for municipality i.
- $\text{Pop}_{j,08}$: Population of municipality j in 1908.

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Robustness: Spillover effects

	Δ Establishments				Δ Mnf. Workers	
	All	w/ Electric Motor	All	w/ Electric Motor	All	
	(1)	(2)	(3)	(4)	(5)	(6)
Electricity Access in 1914	0.321***	0.563***	2.30*	1.49***	38.6***	134.6***
	(0.091)	(0.064)	(1.21)	(0.480)	(7.99)	(50.5)
Neighborhood Access	0.006	0.026	-0.850	-0.373*	4.18	-37.4
	(0.092)	(0.059)	(0.548)	(0.212)	(7.24)	(23.5)
Model	OLS	OLS	IV	IV	OLS	IV
Prefecture FE	✓	✓	✓	✓	✓	✓
Geography	✓	✓	✓	✓	✓	✓
Pop. density 1908	✓	✓	✓	✓	✓	✓
Streamflow	✓	✓	✓	✓	✓	✓
Ruggedness	✓	✓	✓	✓	✓	✓
Observations	10,098	10,098	10,098	10,098	10,098	10,098
First KP-stat			36.0	36.0		36.0
Mean of dep.var	0.30	0.37	0.30	0.37	25.2	25.2

Notes: Robust standard errors clustered by municipalities within 30km radius, following Conley (1999), are reported in parentheses. *, **, and *** indicate significance at the 10%, 5%, and 1% levels.