

# Connecting to Electricity: Technical Change and Regional Development

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# Structural transformation in early 20th-century

- Structural transformation and socio-economic change during electrification.
  - Growth of manufacturing activities (Mumford, 1934, Gordon, 2017, Gaggl et al., 2021).
  - The Second Industrial Revolution.
- Technical change from the steam engine to the electric motor:
  - General purpose technology (Bresnahan and Trajtenberg, 1995).
  - Rapid diffusion and replacement, e.g.,  $\approx 30$  years in Japan.
  - $\leftrightarrow$  Many beneficial technologies, e.g., steam engine (Juhász et al., 2024b).
- Seems to be crucial, but we know little about this technical change.
  - What was the driving force?
  - Whether the timing affects the regional development (first-adopter advantage)?

# This project: Popularization of powered factory

- Electric motors lower barriers to entry in the mnf. 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.
  - Growth of manufacturing activities.
- Explore this hypothesis in early 20th-century Japan by combining:
  - **Newly digitized official records** of establishment-level data and electricity access.
  - **Empirical strategy** exploiting geographical suitability of hydropower generation.
- **Key findings:**
  1. Electricity access increased # establishments and manufacturing workers.
  2. New entrants attributed 80% of this manufacturing growth (w.r.t. workers).
  3. Regions with earlier electricity access enjoyed larger economic development, even today.

# 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* associates 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: **plough** (Alesina et al., 2013), **printing press** (Dittmar, 2011) **steam engine** (Yamasaki, 2023), **tractor** (Kitamura, 2022).

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## 3. Industrialization in Japan:

- Electric motors favored the growth of small-scale industries (Minami, 1979).
- Sussman and Yafeh (2000), Bernhofen and Brown (2004), Tang (2014), Morck and Nakamura (2018) Braguinsky et al. (2021), Tang and Basco (2023) Yamasaki (2023), Ichimura et al. (2024), Juhász et al. (2024a).

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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

A tale of electricity access

From steam engine to electric motor

### Empirical Strategy

Data

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## Results

Main result & Mechanism

Long-run effects

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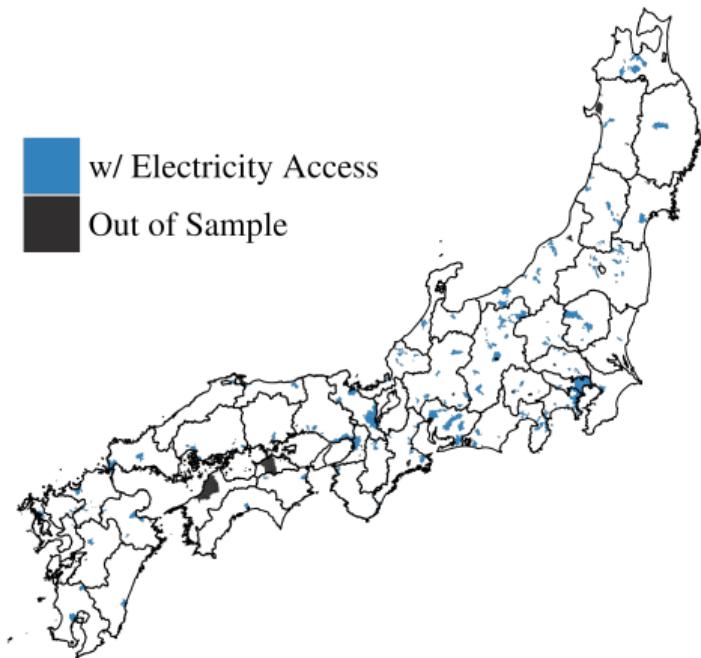
Long-run effects

# Expansion of electricity grids in early 20th Japan

- In the 1880s, electricity supply began in large cities mainly for lighting.
  - Supplied by electric utility companies.
  - Small-scale/high cost of thermal power generation.
  - Modest expansion of electricity supply areas.
- After 1905, the rapid expansion of electricity supply areas due to: (Kurihara, 1964)
  1. Development of long-distance transmission technology.
  2. Low electricity price from hydroelectric power.
  - → Dramatic increase in electricity demand from manufacturing sectors.
- By 1929, over 95% of municipalities got electricity access.

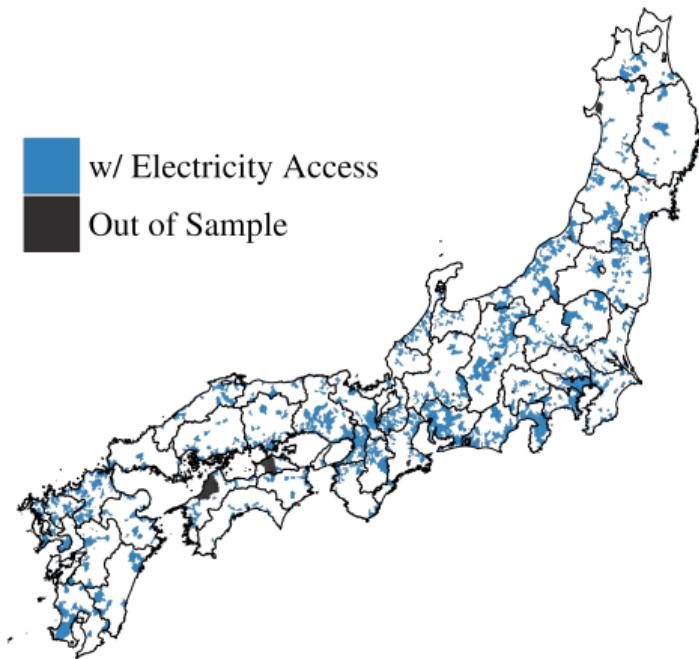
# Expansion of electricity grids

Electricity Grids in 1909



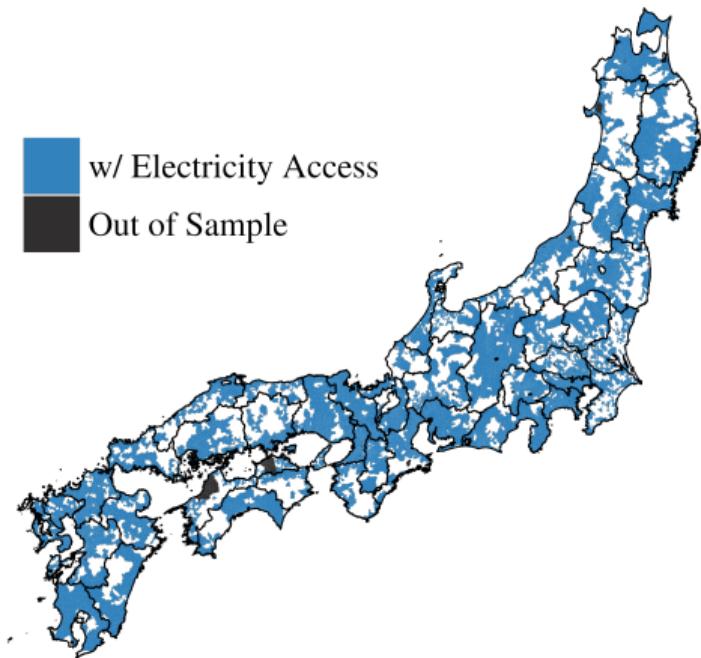
# Expansion of electricity grids

Electricity Grids in 1914



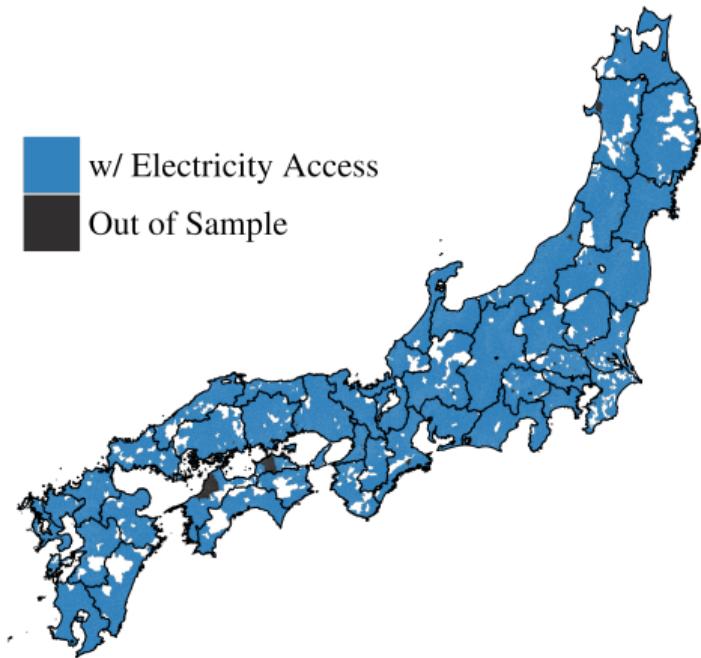
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Electricity Grids in 1919



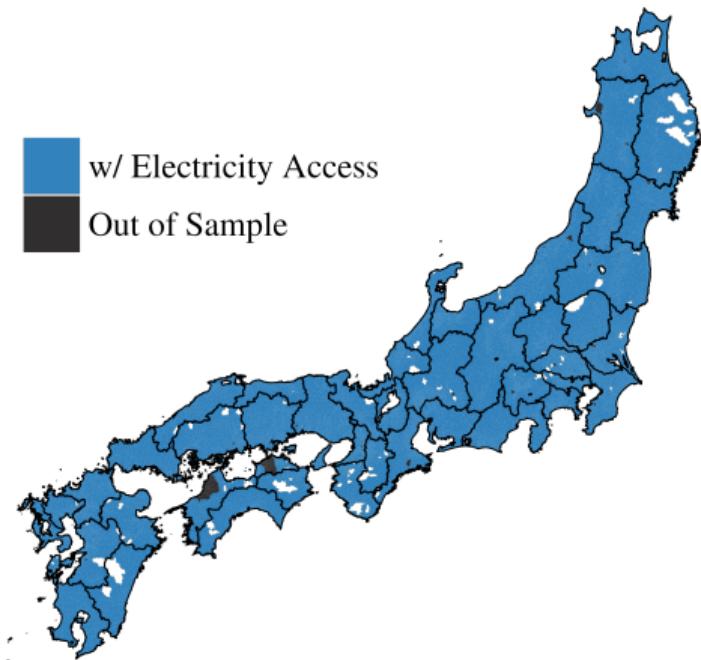
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Electricity Grids in 1924

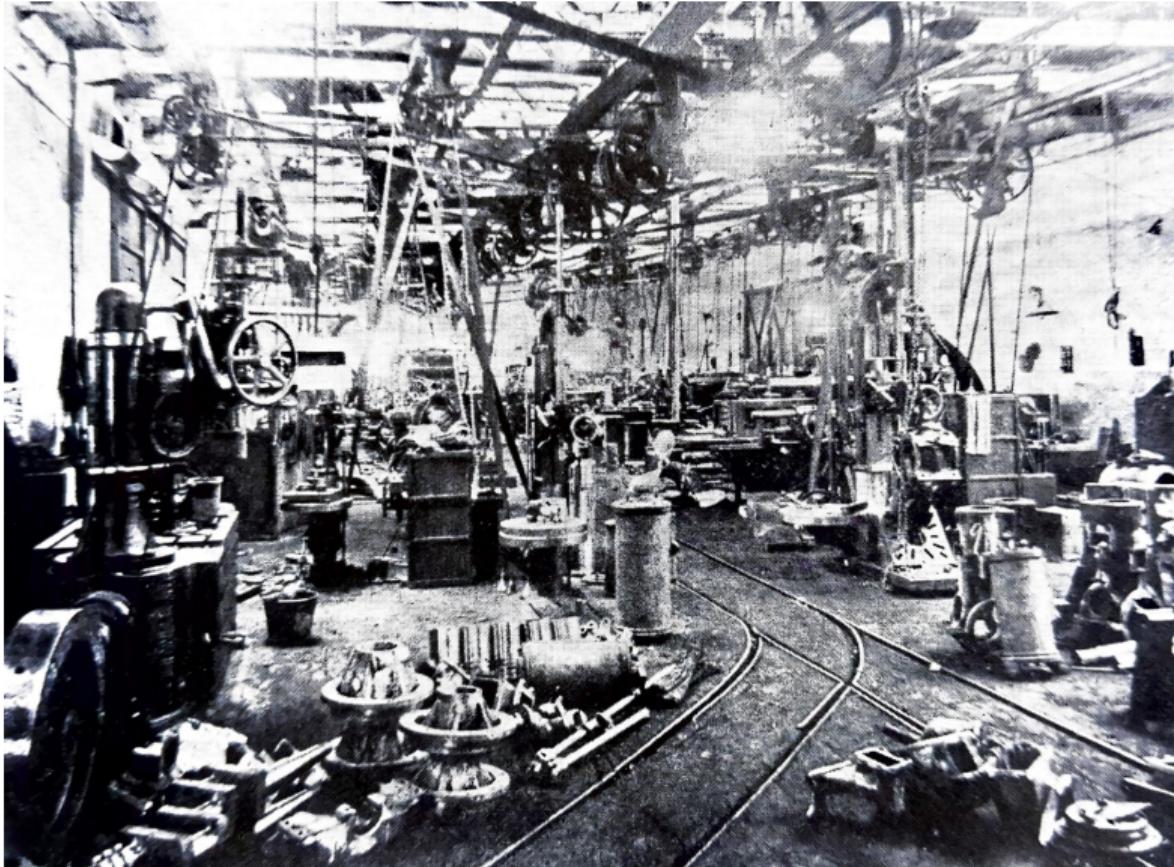


# Expansion of electricity grids

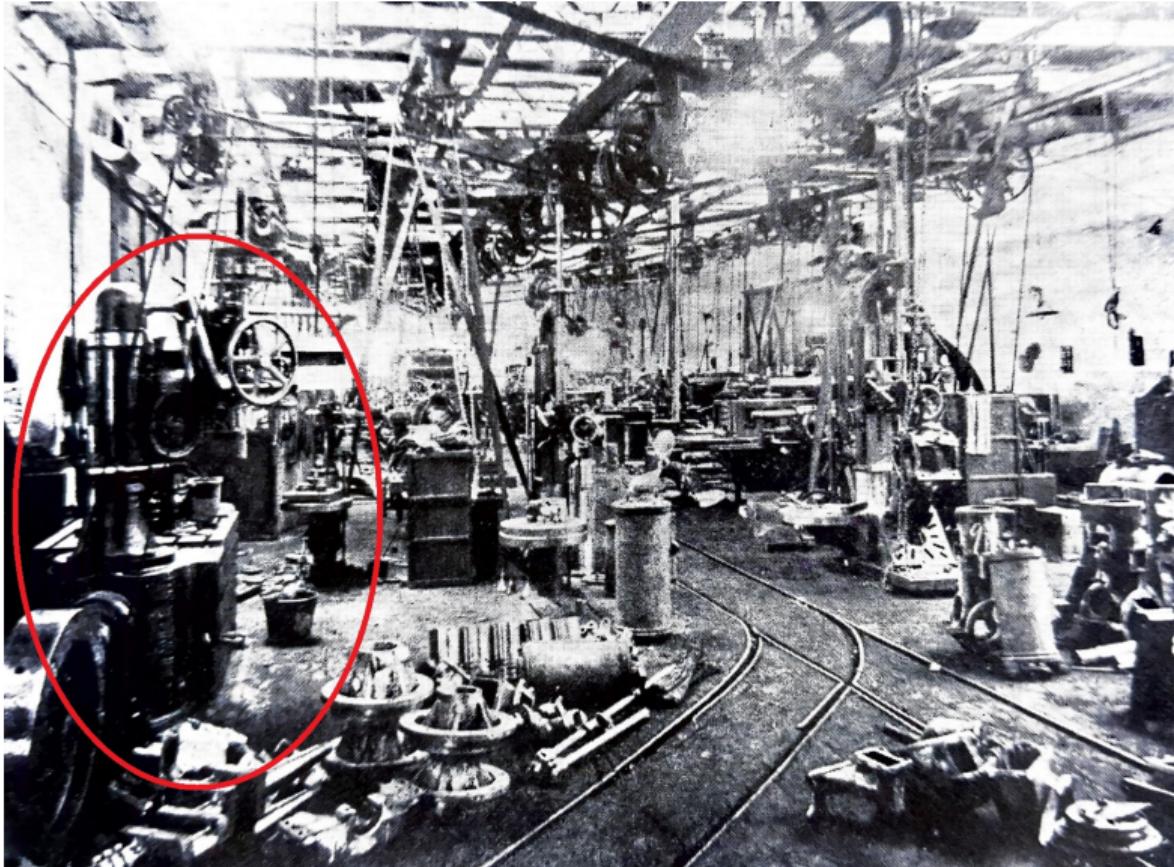
Electricity Grids in 1929



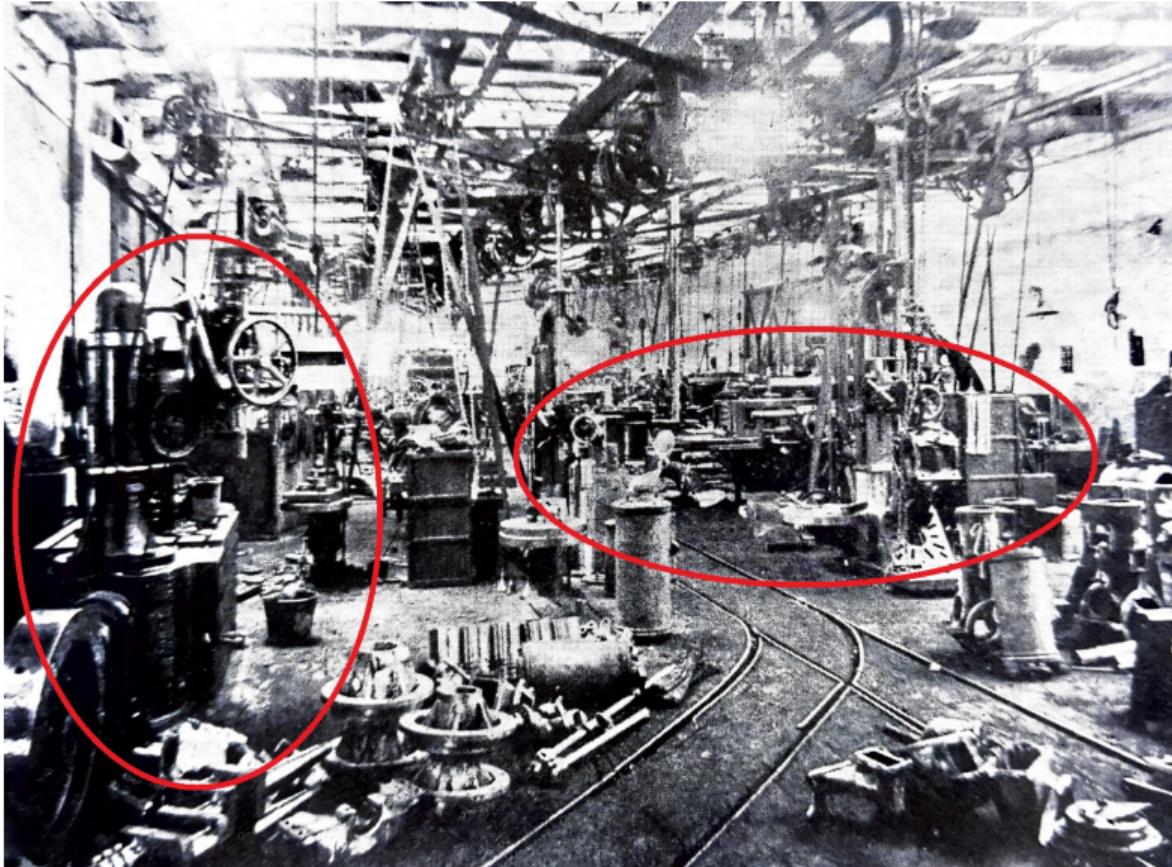
## Steam engine entails high fixed cost (*Group drive system*)



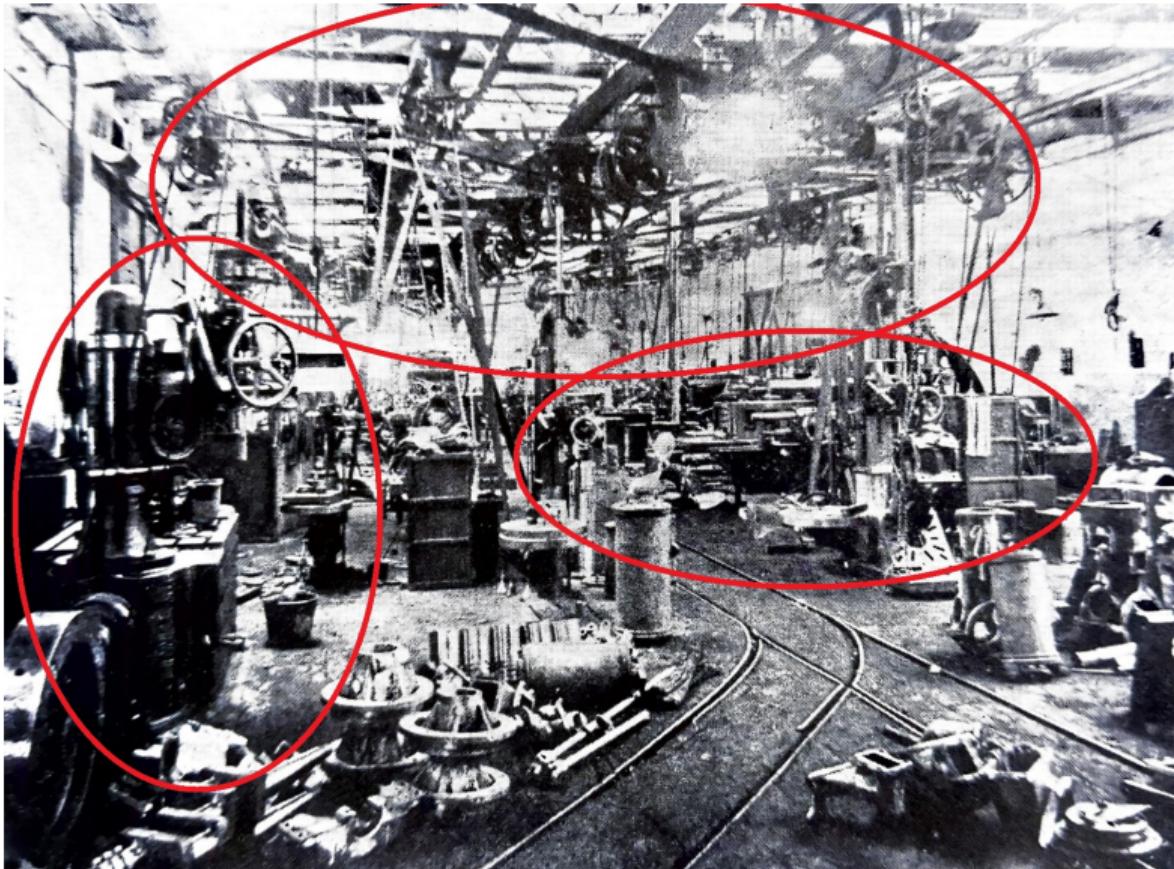
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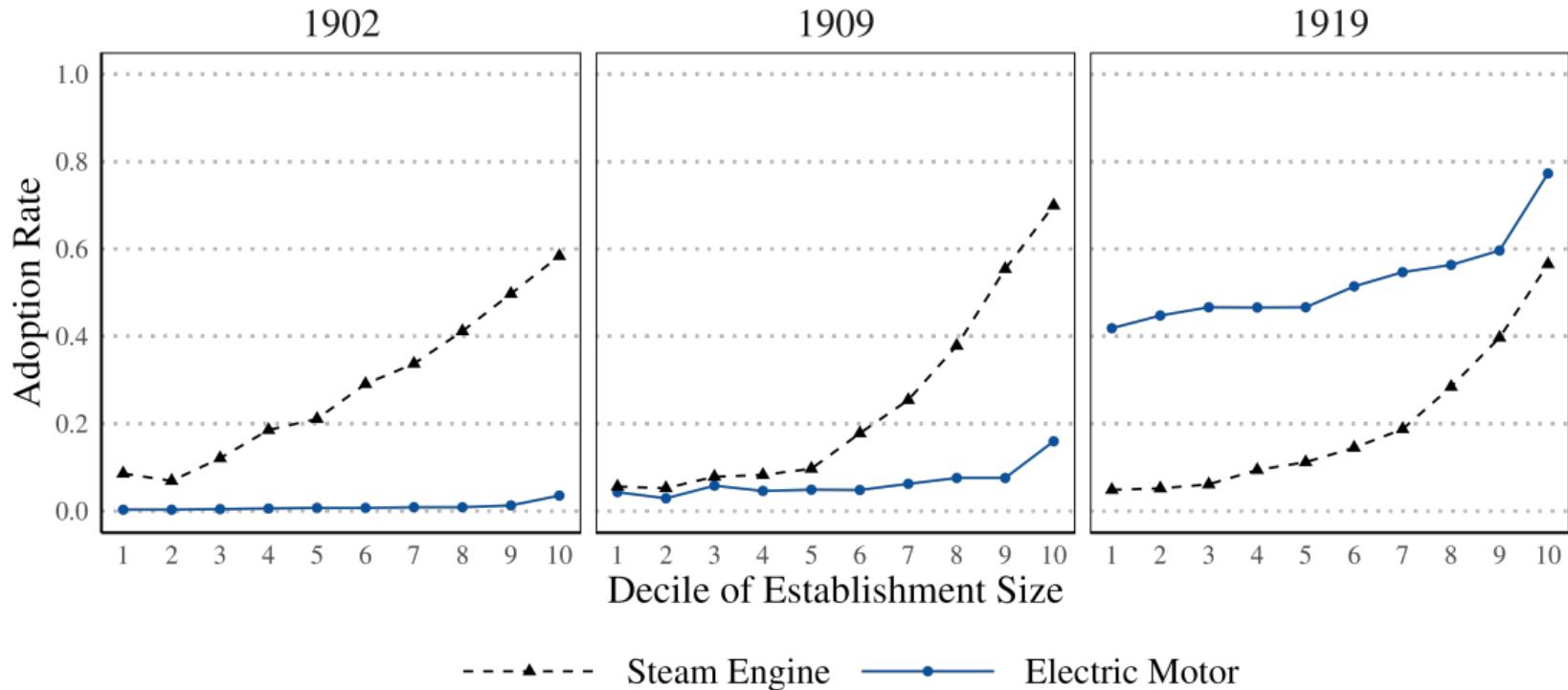
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# Popularization of powered factory



► Transition by industry

► Textile

► Machinery

► Metal

► Food

► Chemical

► Miscellaneous

# Outline

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# Data: Newly digitized official records

## 1. Handbook of Factory (*Kojo Turan*):

- All est. with 10+ workers (1902, 1909, 1916, 1919).
- # male/female workers, # and HP of power source, industry, founded year, and address.
- # establishments: 11,914 in 1909, 23,004 in 1919.

## 2. Handbook of Electric Utility Industry (*Denki Jigo Yoran*):

- Published every year and provides the license status of each electric utility company.
- Digitization every five years after 1909 (municipality-level).
- Location of the power stations.

## 3. Other economic outcomes:

- Population census in early 20th-century.
- Orbis firm database for today's economic activities.

## IV: Hydropower potential

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

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

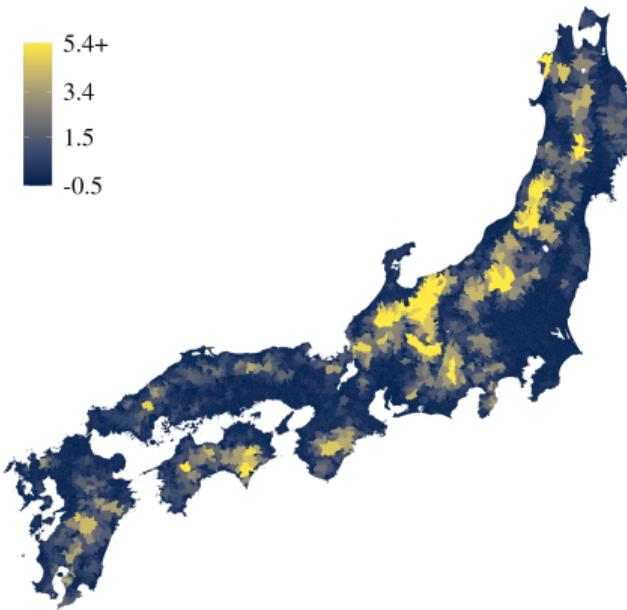
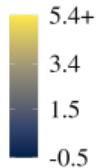
- Power generation depends on streamflow and hydraulic head (Basso and Botter, 2012).
  - Water Volume Index $_j$ : Cumulative annual flow volume of basin  $j$ .
  - Hydraulic Head Height $_j$ : Elevation difference between the basin and areas within a 1km.
- Arai et al. (2022) estimates the  $W_i$  for small-sized basins ( $\approx 10\text{ km}^2$ ) in Japan with
  - 176 basin geographical characteristics.
  - 389 basins with discharge records (ave. 17.1 years).
  - Neural network model.

# Geographical distribution of hydropower potential



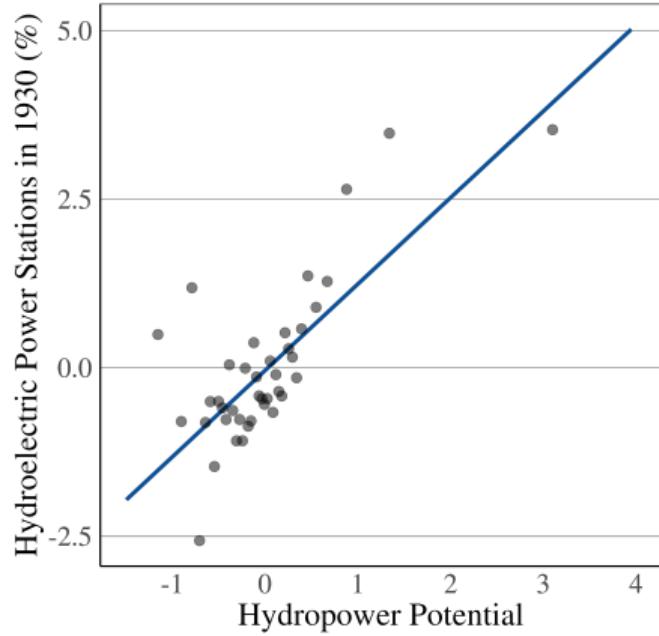
(a) Topography

Hydropower Potential

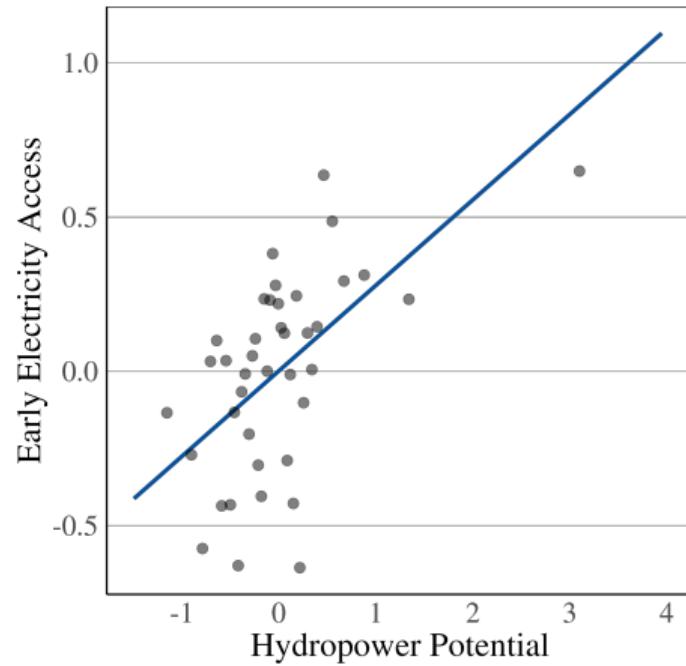


(b) Hydropower potential

# Hydropower potential, hydroelectric generation, and early access



(a) Hydroelectric generation



(b) Early electricity access

# Hydropower potential and economic activities

$$Y_{it} = \sum_{t \neq 1909} \beta_t \text{Hydropower Potential}_i \times \mathbf{1}\{\text{Year} = t\} + \\ \sum_{t \neq 1909} \lambda_t \ln(\text{PopDens}_{i, 1908}) \times \mathbf{1}\{\text{Year} = t\} + \\ \sum_{t \neq 1909} \gamma_t \text{Geography}_i \times \mathbf{1}\{\text{Year} = t\} + \alpha_i + \delta_t + v_{it},$$

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

# Hydropower potential matters only after the grid expansion

	Number of Establishments					
	Total			w/ Electric Motor		
	(1)	(2)	(3)	(4)	(5)	(6)
Hydropower Potential × 1902	-0.024 (0.022)	-0.020 (0.023)	-0.004 (0.023)	-0.001 (0.001)	-0.001 (0.001)	-0.001 (0.001)
Hydropower Potential × 1916	0.015 (0.016)	0.023 (0.016)	0.018 (0.017)	0.047*** (0.007)	0.044*** (0.007)	0.040*** (0.008)
Hydropower Potential × 1919	0.091** (0.036)	0.090** (0.037)	0.080** (0.038)	0.101*** (0.014)	0.093*** (0.013)	0.081*** (0.013)
Streamflow × Year FE		✓	✓		✓	✓
Ruggedness × Year FE			✓			✓
Observations	40,020	40,020	40,020	40,020	40,020	40,020
Adjusted R <sup>2</sup>	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:** \*, \*\*, and \*\*\* indicate significance at the 10%, 5%, and 1% levels. Robust standard errors clustered at the municipality level are reported in parentheses.

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# Main Specification

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

- $i$ : municipality w/o electricity supply in 1909,  $p$ : prefecture.
- $\Delta Y_{ip}$ : 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.
- $\text{Geography}_i$ : Area size, dist. to the coast, and dist. metropolis.
- $\tau_p$ : prefecture fixed effects.

► 1st stage

## 2nd stage: Effect of electricity access on industrialization

	$\Delta$ Number of Establishments (1909-1919)				Demographics	
	Total	w/ Electric Motor	Total	w/ Electric Motor	$\Delta$ Mnf. Workers (1909-1919)	$\Delta$ Pop. (1908-1918)
	(1)	(2)	(3)	(4)	(5)	(6)
Electricity Access in 1914	0.307*** (0.090)	0.559*** (0.064)	2.00** (1.02)	1.29*** (0.404)	121.7*** (43.3)	165.6 (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:** 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.

# Main result: Robustness

- **Placebo test** ▶ Placebo

- Concern about unobserved preexisting regional characteristics.
- Replacing the outcome with the change in 1902-1909 (= before the access).
- → Much smaller and insignificant effect.

- **Railway access** ▶ Railway

- Railway access may induce technology adoption through market access (Yamasaki, 2023).
- Including  $\Delta$  in the dist. to the railway station as a control.
- → Nearly identical and still statistically significant.

- **Infrastructure investment** ▶ Infrastructure

- Infrastructure investment (e.g., dams) may spur manufacturing (Kline and Moretti, 2014).
- Excluding the municipalities with large hydropower stations in 1930.
- → Slightly smaller but still statistically significant.

# Entrants drove manufacturing growth

	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** (1.02)	2.69*** (0.858)	0.277 (0.215)	0.273 (0.170)	1.29*** (0.404)	0.909*** (0.265)	121.7*** (43.3)	105.3*** (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:** 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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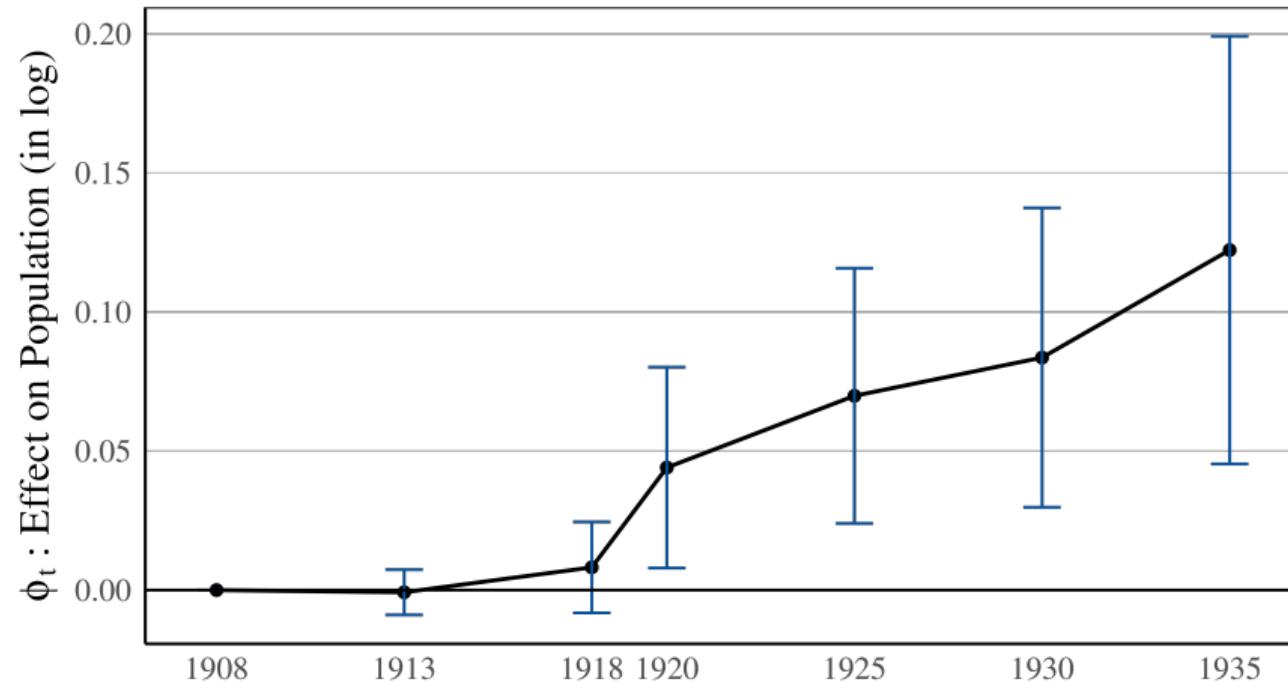
# Population growth after electrification

2nd stage:

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

- $i$ : municipality w/o electricity supply in 1909,  $p$ : prefecture,  $t$ : year.
- $\text{Population}_{it}$ : Population in municipality  $i$  in year  $t$ .
- $\text{Early Electricity Access}_i$ : 1929 minus the year of first electricity access
- $\ln(\text{PopDens}_{i,1908})$ : Log of population density in 1908.
- $\text{Geography}_i$ : Area size, dist. to the coast, and dist. metropolis.
- $\zeta_{pt}$ : prefecture-year fixed effects.

## First-adopter advantage



**Notes:** 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.

# Long-run effect: Economic activities today

	Num. of Firms		Num. of Emp.		Ave. Sales		Sales/Emp.	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Early Electricity Access	0.057*** (0.004)	0.158* (0.084)	0.066*** (0.005)	0.185* (0.103)	0.024*** (0.003)	0.095* (0.054)	0.010*** (0.002)	0.067* (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:** 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.

# Conclusion

- Summary of this project:
  - Electricity access stimulated manufacturing activities, in particular w/ electric motors.
  - This manufacturing growth was driven by new entrants.
  - In addition, regions w/ earlier access enjoyed higher population growth.
  - Today, these regions have more firms, higher sales, and more employees.
- Future works:
  - Productivity changes depending on the establishment size.
  - Detailed mechanisms behind the persistent effects.
  - (e.g., agglomeration of small-scale industry).

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## Reference III

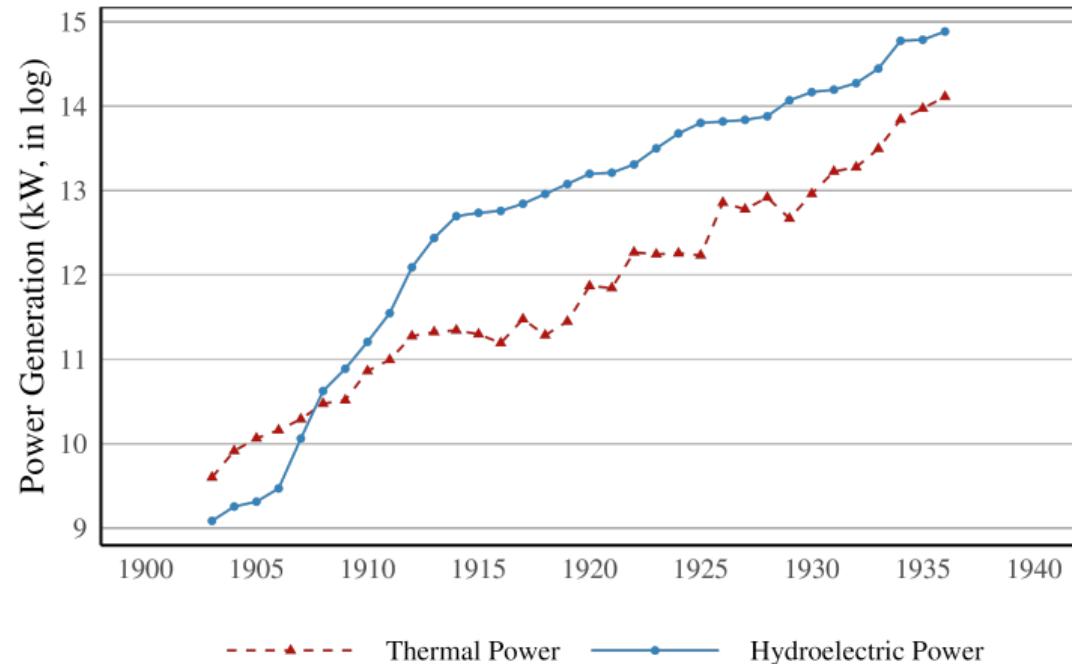
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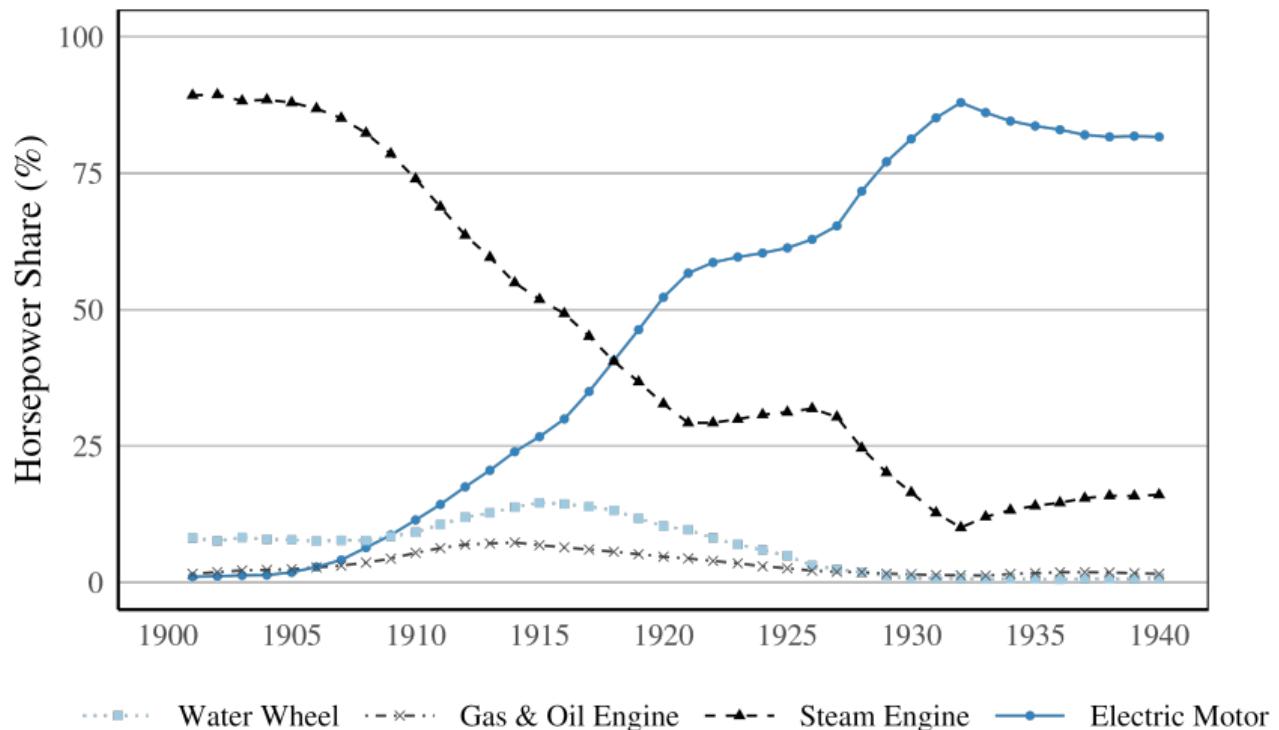
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# Source of power generation

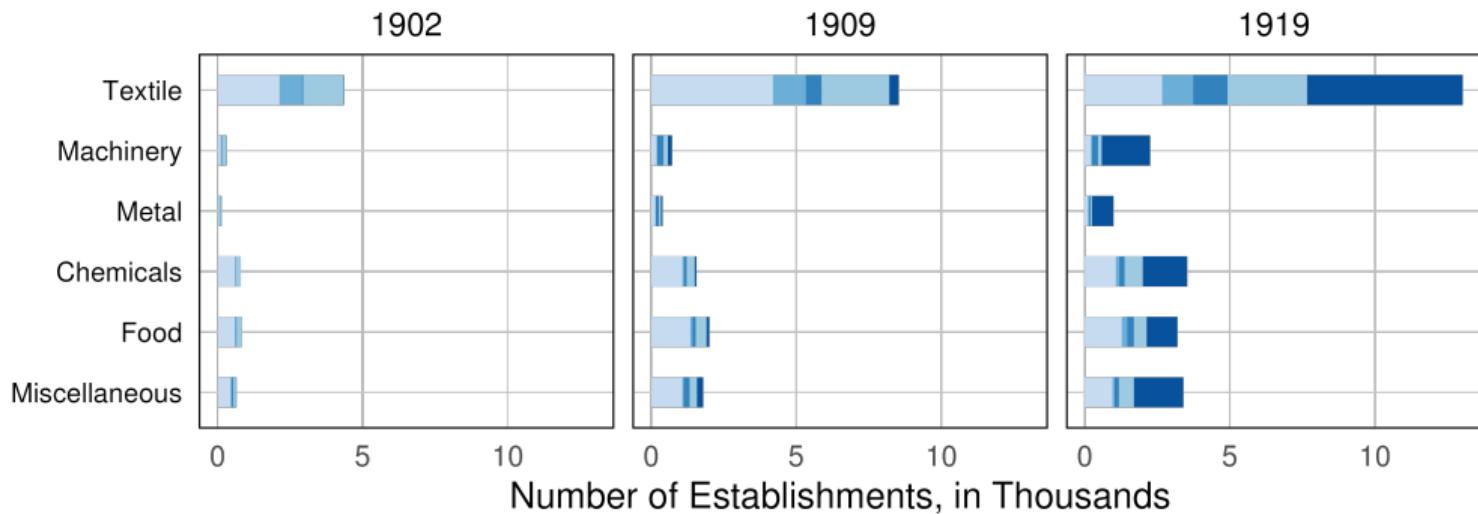
Figure: Source of Power Generation



# Transition of power source



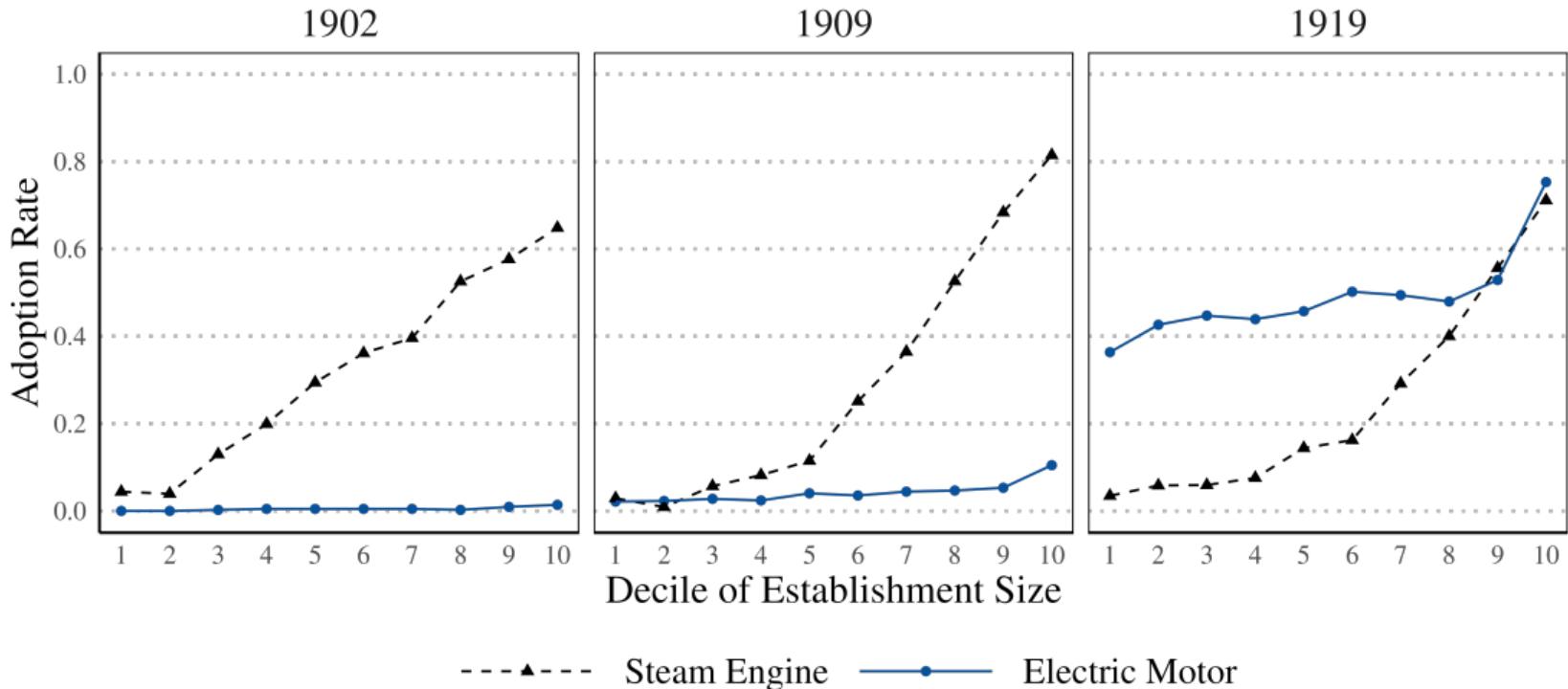
# Power source transition by industry



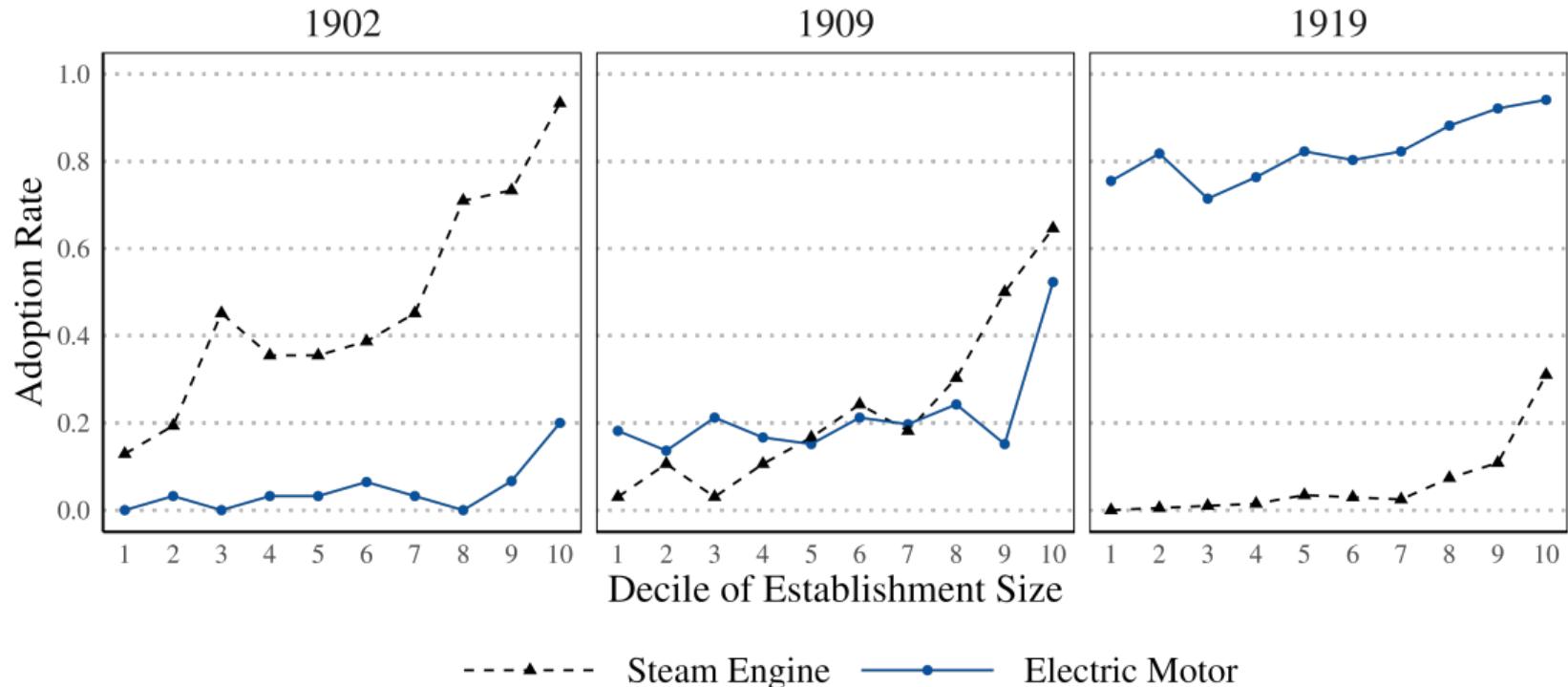
Power Source

- Electric Motor
- Steam Engine
- Gas/Oil Engine
- Water Wheel
- Hands only

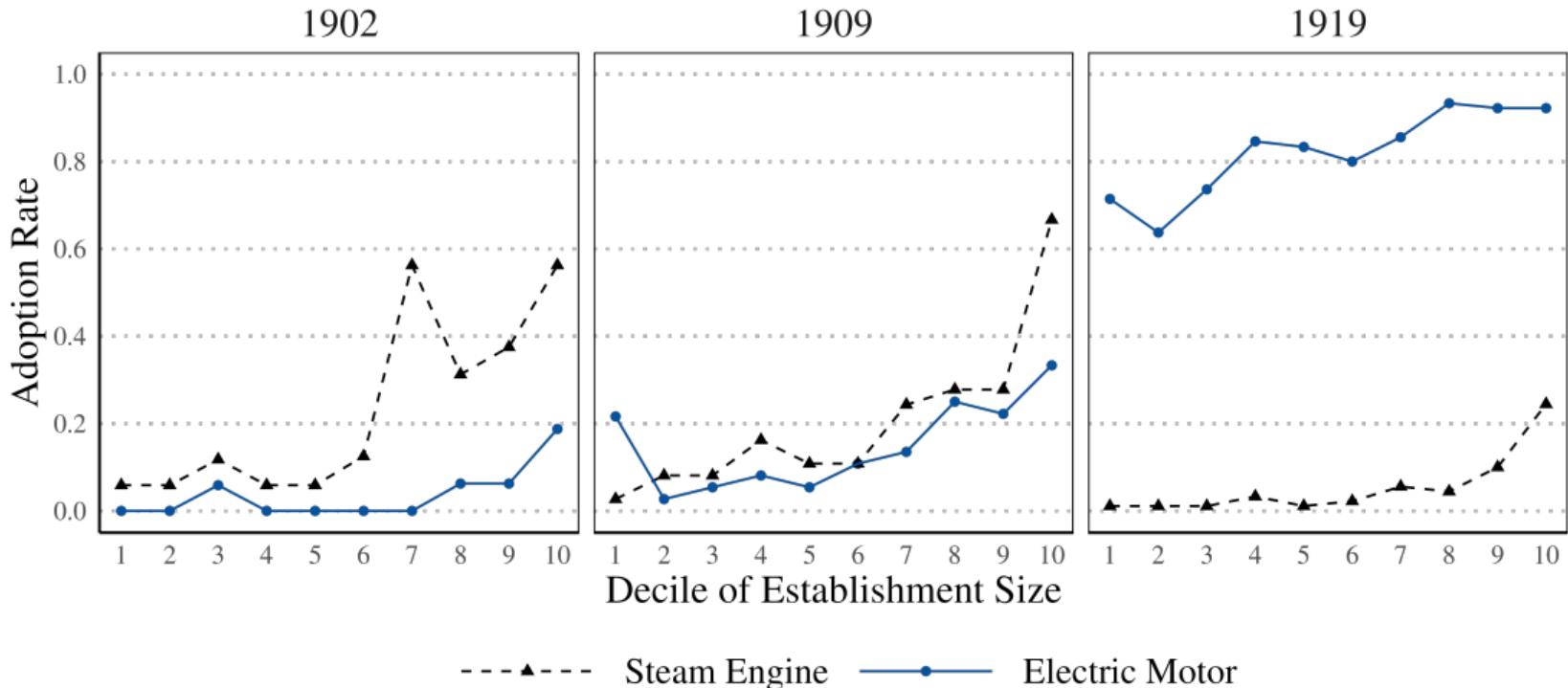
# Popularization of powered factory (Textile)



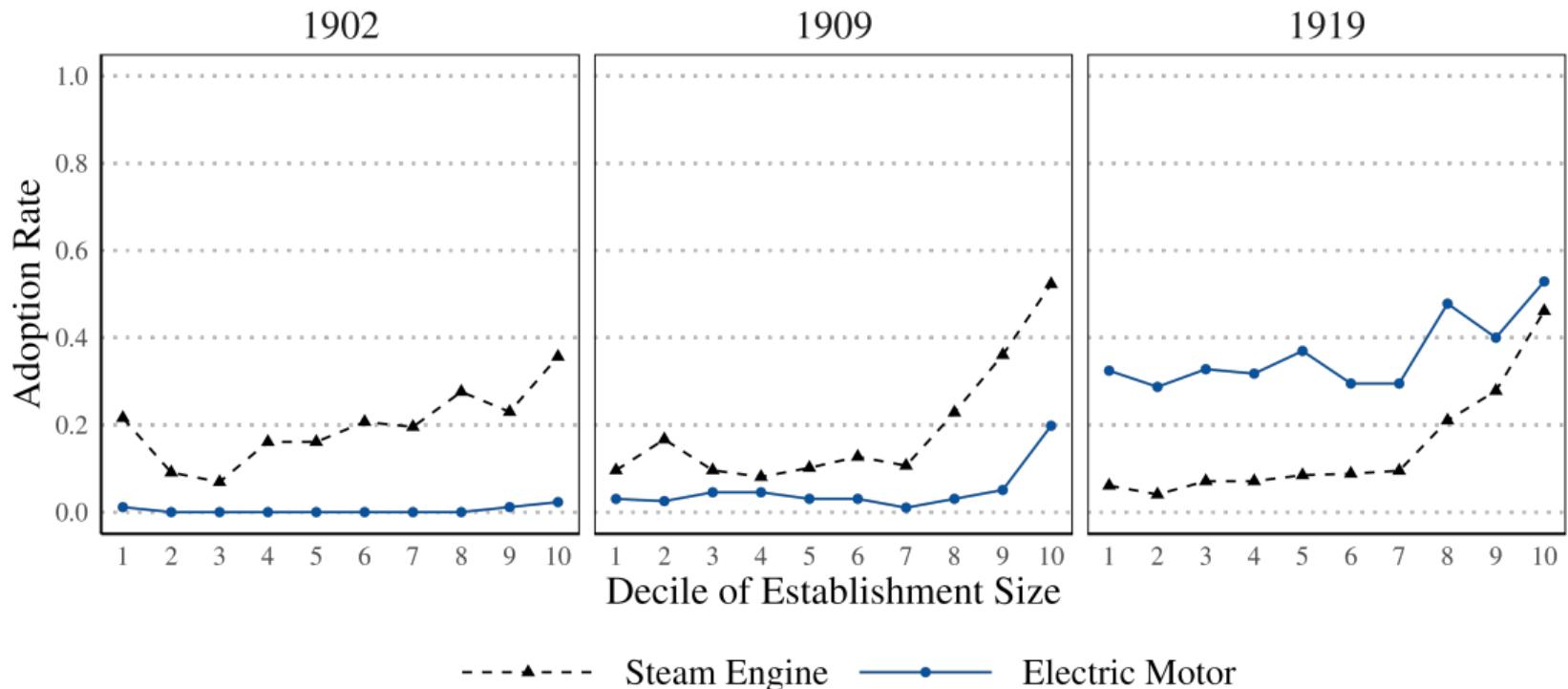
# Popularization of powered factory (Machinery)



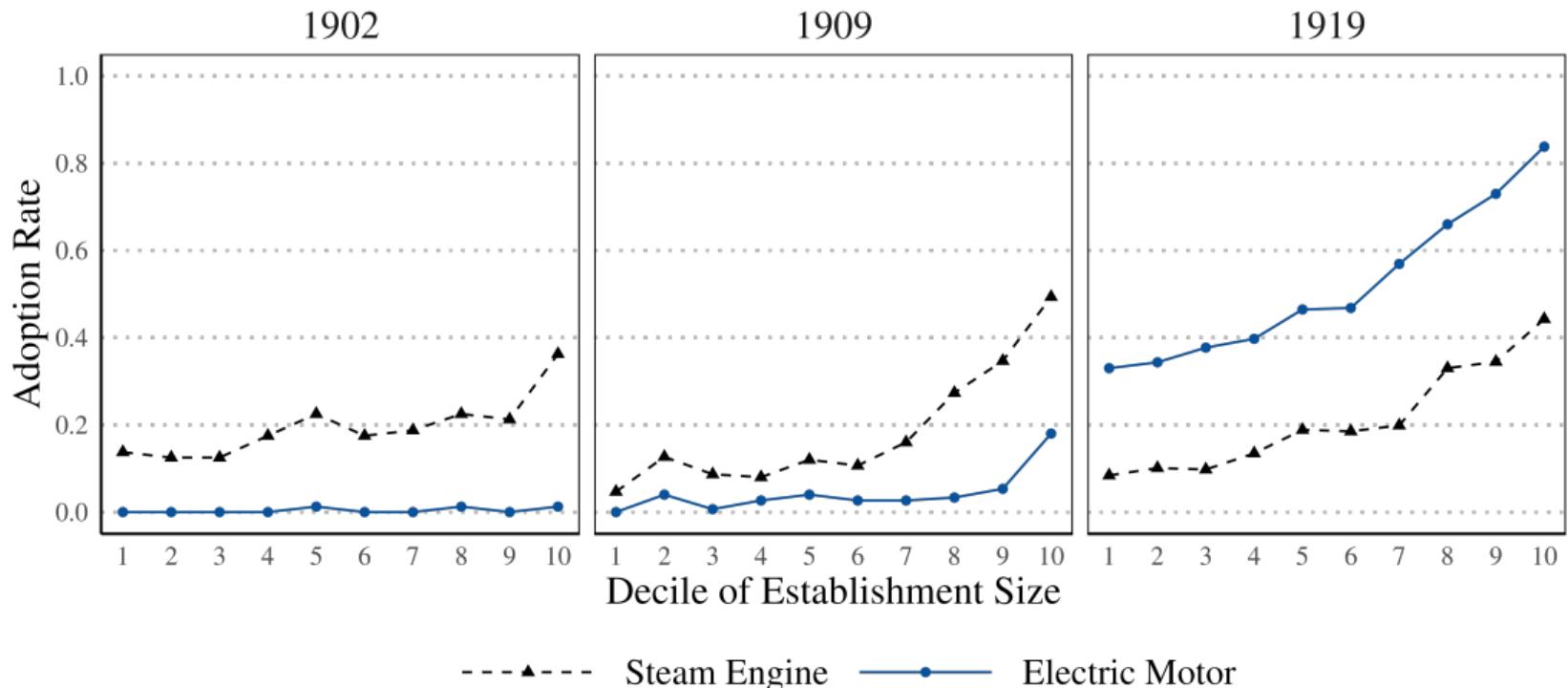
# Popularization of powered factory (Metal)



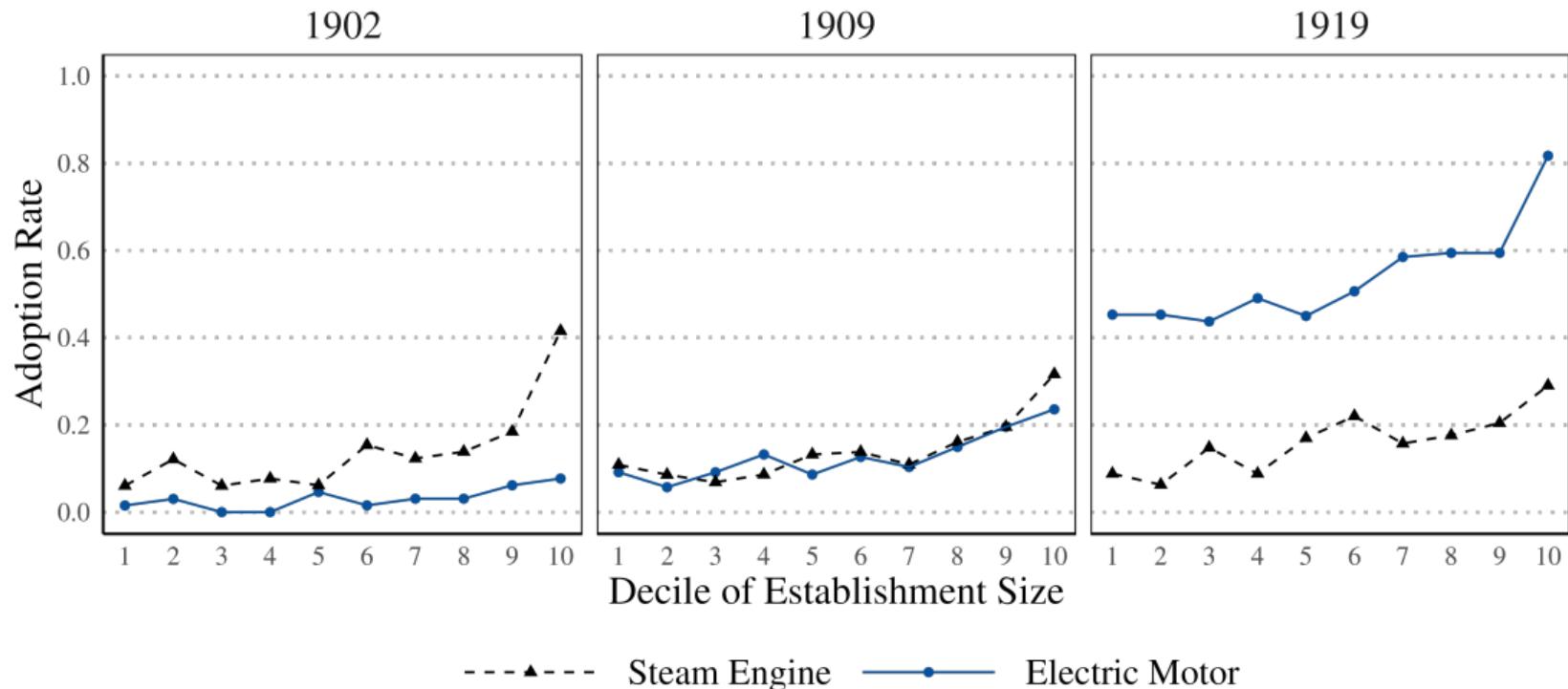
# Popularization of powered factory (Food products)



# Popularization of powered factory (Chemicals)



# Popularization of powered factory (Miscellaneous)



## Hydropower potential and economic activities

$$Y_{it} = \sum_{t \neq 1909} \beta_t \text{Hydropower Potential}_i \times \mathbf{1}\{\text{Year} = t\} + \\ \sum_{t \neq 1909} \lambda_t \ln(\text{PopDens}_{i,1908}) \times \mathbf{1}\{\text{Year} = t\} + \\ \sum_{t \neq 1909} \gamma_t \text{Geography}_i \times \mathbf{1}\{\text{Year} = t\} + \alpha_i + \delta_t + v_{it},$$

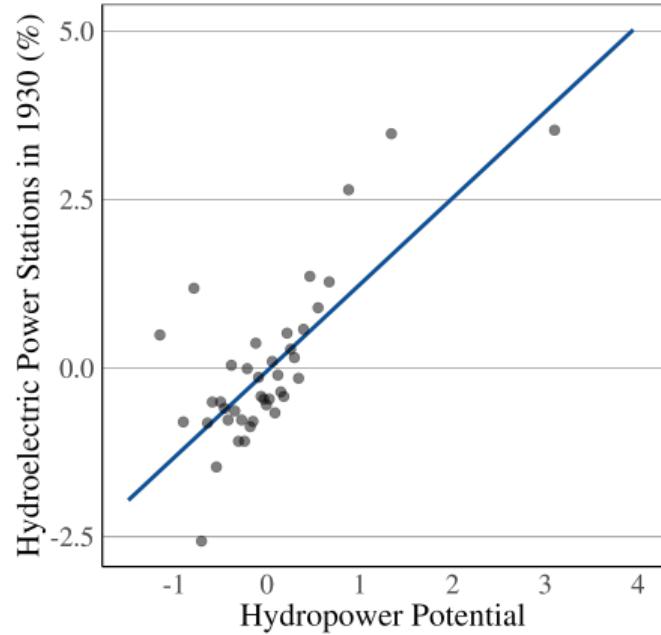
- $i$ : municipality where electricity supply began after 1909.
- $t \in \{1902, 1909, 1916, 1919\}$ : year.
- $Y_{it}$ : # establishments.
- $\text{Hydropower potential}_i$ : Suitability for hydropower generation.
- $\text{Geography}_i$ : Area size, dist. to the coast, and dist. metropolis.
- $(\alpha_i,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

# Hydropower potential matters only after the grid expansion

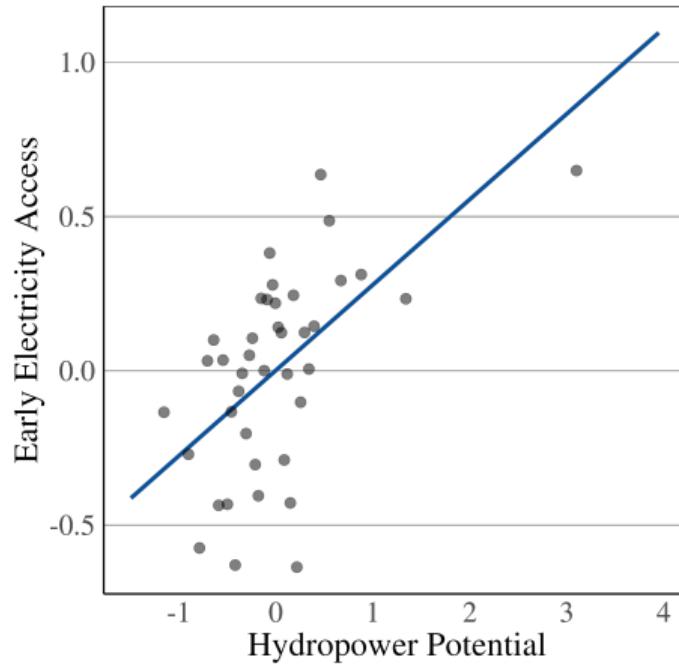
	Number of Establishments					
	Total			w/ Electric Motor		
	(1)	(2)	(3)	(4)	(5)	(6)
Hydropower Potential × 1902	-0.024 (0.022)	-0.020 (0.023)	-0.004 (0.023)	-0.001 (0.001)	-0.001 (0.001)	-0.001 (0.001)
Hydropower Potential × 1916	0.015 (0.016)	0.023 (0.016)	0.018 (0.017)	0.047*** (0.007)	0.044*** (0.007)	0.040*** (0.008)
Hydropower Potential × 1919	0.091** (0.036)	0.090** (0.037)	0.080** (0.038)	0.101*** (0.014)	0.093*** (0.013)	0.081*** (0.013)
Streamflow × Year FE		✓	✓		✓	✓
Ruggedness × Year FE			✓			✓
Observations	40,020	40,020	40,020	40,020	40,020	40,020
Adjusted R <sup>2</sup>	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:** \*, \*\*, and \*\*\* indicate significance at the 10%, 5%, and 1% levels. Robust standard errors clustered at the municipality level are reported in parentheses.

# Hydropower potential, hydroelectric generation, and early access



(a) Hydroelectric generation



(b) Early electricity access

# First stage

	Electricity Access in 1914			Early Electricity Access		
	(1)	(2)	(3)	(4)	(5)	(6)
Hydropower Potential	0.041*** (0.007)	0.042*** (0.007)	0.041*** (0.007)	0.216*** (0.074)	0.219*** (0.076)	0.250*** (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 <sup>2</sup>	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:** 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.

# Main result: Placebo test

	Δ Number of Establishments (1902-1909)				Demographics Δ Mnf. Workers (1902-1909) (5)
	Total (1)	w/ Electric Motor (2)	Total (3)	w/ Electric Motor (4)	
Electricity Access in 1914	0.395*** (0.083)	0.004** (0.002)	0.176 (0.693)	0.012 (0.016)	24.4 (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:** 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.

# Main result: Railway access

	Δ Number of Establishments (1909-1919)				Demographics	
	Total (1)	w/ Electric Motor (2)	Total (3)	w/ Electric Motor (4)	Δ Mnf. Workers (1909-1919) (5)	Δ Pop. (1908-1918) (6)
	(0.088)	(0.062)	(1.04)	(0.409)	(44.7)	(376.8)
Electricity Access in 1914	0.298*** (0.088)	0.551*** (0.062)	2.02* (1.04)	1.29*** (0.409)	122.5*** (44.7)	156.0 (376.8)
Δ Railway Access	-0.038 (0.044)	-0.034 (0.026)	0.036 (0.070)	-0.002 (0.032)	2.19 (3.13)	-28.4 (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:** 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.

# Main result: Infrastructure investment

	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*** (0.090)	0.560*** (0.064)	1.34* (0.771)	1.32*** (0.395)	90.0** (40.8)	121.1 (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:** 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.

# Long-run effect: Economic activities today

	Num. of Firms		Num. of Emp.		Ave. Sales		Sales/Emp.	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Early Electricity Access	0.057*** (0.004)	0.158* (0.084)	0.066*** (0.005)	0.185* (0.103)	0.024*** (0.003)	0.095* (0.054)	0.010*** (0.002)	0.067* (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:** 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.