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The long-run gains from the early adoption of electricity

Björn Brey

GEP

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Björn Brey †
Université Libre de Bruxelles (ECARES)

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Abstract

This paper explores the effect of the early adoption of technology on local economic development. While timing and intensity of technology adoption are key drivers of economic divergence across countries, the immediate impact of new technologies within advanced countries has been elusive. Resolving this puzzle, this paper documents that the early adoption of electricity across late 19th century Switzerland was conducive to local economic development not just in the short-run, but also in the long-run. Exploiting exogenous variation in the potential to produce electricity from waterpower combined with rapid changes in power generation and transmission technology the evidence presented can plausibly be interpreted as causal. The main mechanism through which differences in economic development persist is increased human capital accumulation and innovation, rather than persistent differences in the way electricity is used.

JEL Classifications: N13, N33, O14, O33
Keywords: Electricity, Industrialization, Long-run development, Human capital

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†Contact Address: ECARES Université Libre de Bruxelles, Ave. F.D. Roosevelt 50, 1050 Brussels, Belgium. Email:bjorn.brey@ulb.be, Homepage: https://sites.google.com/view/bjoernbrey

1 Introduction

The adoption of new technologies is viewed as being at the core of economic development. The timing and intensity of adoption is associated with a drastic divergence in incomes across countries.[1] Despite this apparent importance of the early adoption of new technologies, its lasting impact within advanced countries remains elusive.[2,3]

This raises the question whether the pattern in which new technologies diffuse is at all important for local development in the long-run, or whether it might even be detrimental when considering some prominent historical examples of technological leadership within countries (e.g. the North of England, the Rust Belt in the USA, and the Ruhr area in Germany). More broadly the unavailability of well-identified within country evidence raises the question whether the early adoption of technology and the divergence in economic development across countries are purely a reflection of underlying cultural, institutional or human characteristics.[4]

This paper studies the role played by the early adoption of new technologies on the spatial evolution of economic development within an advanced country. In particular, I study (i) the extent to which the early adoption of a new technology led to contemporaneous economic development,[5] (ii) whether differences continued to persist even as the technology became widely adopted and (iii) the mechanisms that can explain this persistent divergence in economic activity. I investigate these three empirical questions in the context of the early adoption of electricity across late 19th century Switzerland.[6]

I find that the initial round of electricity adoption had a considerable effect on structural transformation. Locations which were able to adopt electricity early experienced an immediate shift in employment from agriculture to manufacturing. Further, areas that had adopted electricity earlier continue to be more industrialized and have higher incomes over 100 years later. This is not just due to an increased level of economic development by 1900, rather outcomes continued to diverge between areas which adopted electricity

[1]The most recent evidence relies on calibrated models using cross-country data (see e.g. Comin & Hobijn 2010; Comin & Mestieri 2018).

[2]Mansfield (1961); David (1990); Jovanovic & Rousseau (2005); Hall & Rosenberg (2010) document the slow diffusion and apparent lack of economic impact of major technologies at early stages of adoption.

[3]The few papers (Lewis & Severnini 2019; Franck & Galor 2019) that have studied the lasting economic impact of technology adoption within advanced countries find minor positive or even considerable negative effects, respectively. However, both papers focussed at late-stages of the technologies diffusion (rural electrification in the 1930s US and steam engines in 1860s France).

[4]See for example, respectively, Mokyr (2016), Acemoglu et al. (2001), Ashraf & Galor (2013).

[5]This has, of course, been documented before. For example, De Pleijt et al. (2018) documents the impact of steam engines 30 years after James Watt's considerable improvements. However, my paper is able to look at a particularly brief and well defined time-window, analysing electricity adoption by 1900 less than 20 years after its first relevant economic application dated between 1882 and 1894 (Jovanovic & Rousseau 2005; Comin & Hobijn 2010).

[6]The following terminology is used here: Adoption of electricity refers to the locally conjoint generation and use of electricity during the early phase of electrification. Individual references to generation or use of electricity refer to the respective component of electrification. Access to electricity refers to the later possibility to use electrical power through the electricity grid without necessarily having local generation.

early and those which did not throughout the first half of the 20th century. This is despite electricity becoming universally available with the expansion of the electricity grid in the early 20th century. Not just access became equal, even differences in the use of electricity disappeared at the latest by 1929. Finally, I find evidence that earlier exposure to electricity led to an immediate increase in human capital accumulation and innovation. This in turn appears to be the main driver of the subsequent economic growth.

Studying the early adoption of new technologies has been difficult, because (i) systematic data is rarely recorded in the early phase of adoption of new technologies, (ii) technology is not randomly allocated, but rather adopted where benefits are largest, and (iii) differences in access to new technologies usually persist over long periods of time. My historical setting allows me to overcome these challenges. First, Switzerland was at the forefront of electricity adoption in the late 19th century and collected systematic data on electricity generation and economic development. Second, the initial ability to adopt electricity depended on idiosyncratic geographical features, as before the creation of an extensive electricity grid in the early 20th century, the use of electricity relied exclusively on locally available waterpower for generation. Notably, this waterpower was also unexploitable with pre-electricity technologies. Third, the differential exposure to electricity was only short-lived as after 1900 long-distance transmission was implemented, which made electricity rapidly available across all of Switzerland. This provides a unique empirical setting in which early adoption of a new technology was effectively randomly assigned to areas for the relatively brief period of about 20 years.

To carry out my analysis, I have assembled detailed information on electricity generation, geographical suitability for electricity generation and measures of economic development from 1860 to the present day (in roughly 20 year intervals) for 178 districts covering the whole of Switzerland. The crucial information on actual and potential electricity generation has been obtained from digitizing and geo-referencing a detailed survey of all existing and potential waterpower plants conducted by Swiss government engineers at the start of the 20th century (see Bossard 1916). The information on economic development is collected from a wide range of sources with the pivotal information on sectoral employment coming from the Swiss censuses 1860-2011 (see Bundesamt für Statistik 1860-2011).

Switzerland's adoption of electricity in the late 19th century provides a unique setting to investigate the causal impact of early technology adoption as adoption was initially as good as random, and those initial differences only mattered for a short period. Electricity from thermal power was unviable in Switzerland at the time due to low thermodynamic efficiency in electricity generation and the high price of imported coal, making waterpower the only economically viable way to generate electricity (Bossard 1916). Importantly, the suitability of areas to generate electricity was based on otherwise unimportant geographical differences (mainly the gradient of a river combined with bends and confluences meaning most potential is located near rocky streams with little economic or geographic significance). Figure 1 illustrates the relationship between electricity generation in 1900 across Swiss districts and the more than 1000 potential locations identified by Bossard (1916) as suitable for electric waterpower plants.[7] As it can be clearly seen, locations are widely dispersed across Switzerland and the available energy potential from them is crucial for the observed electricity generation by 1900.

Further, these geographical features are unrelated to the location of pre-electricity watermills as mechanical transmission was unable to exploit the gigantic amounts of energy these features could provide.[8] Consistent with this I demonstrate that these geographical features were irrelevant before the commercial use of electricity by showing that i) there is no relationship between the potential for electricity generation and the mechanical energy generated by watermills in 1880, ii) no relationships to the level of economic development by 1880 and iii) no divergence in trends between 1860-1880. These geographical features also only mattered for the use of electricity for the initial 20 year period from 1880 till 1900, as in this period, electricity had to be consumed near the power source as transmission over long distances was unfeasible. From 1900 onwards this constraint was rapidly relaxed as long distance transmission lines were established from where electricity was most efficiently produced to wherever there was demand.[9] This provides a unique empirical setting in which the exposure to electricity was effectively randomly assigned to areas for about 20 years. Before and after this period areas had instead access to the same technology.

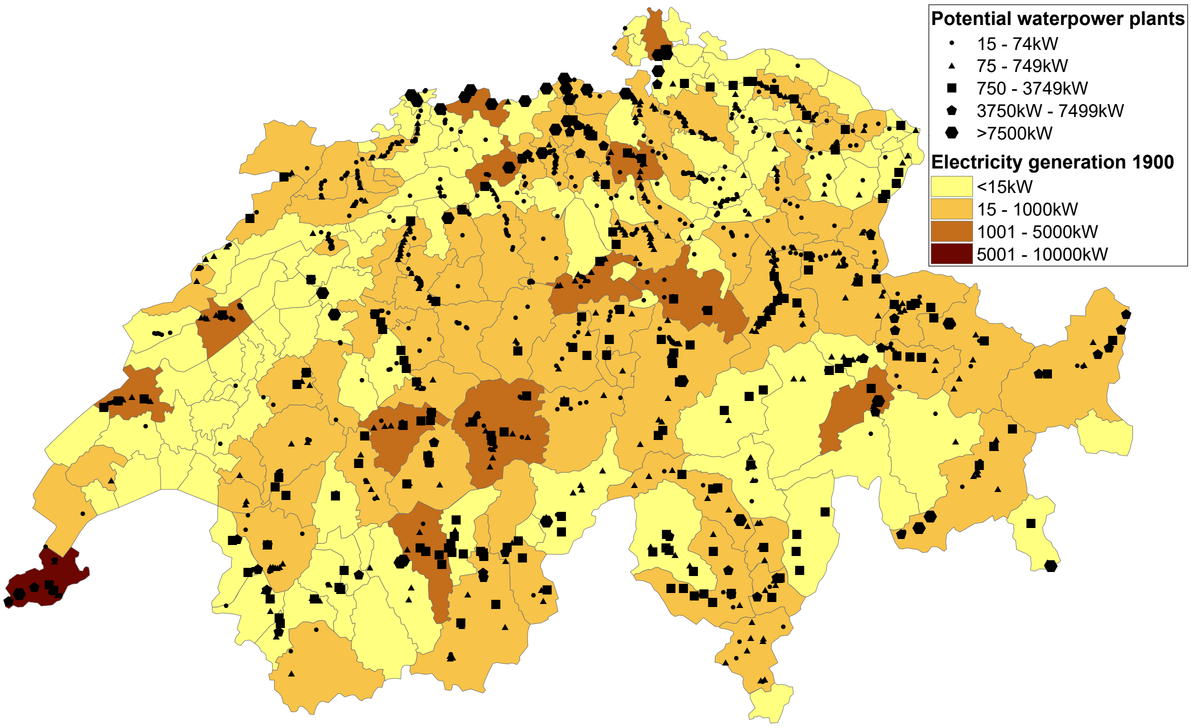
My claim is that the observed divergence in economic development up to today emerged solely due to the brief period in which electricity adoption differed across areas. An interesting question is whether the effect of electricity on industrial employment came from the need for its provision or from its use in the production process. This relates to De Pleijt et al. (2018) who suggest that the production, operation and maintenance of new steam engines led to the formation of new skills during the industrial revolution, while their use in the production process is viewed as inherently deskilling (Berg 2005). Electricity is perfect to study the employment effect as in contrast to steam engines, where provision and use had to be integrated within the same firm, the provision of electricity developed into a unique industry, i.e. electricity generation and distribution. I find that

[7]The engineers surveying these potential locations across the whole of Switzerland aimed to provide the optimal network of waterpower plants for energy generation based on the available geographic characteristics explicitly disregarding any pre-existing developments and economic considerations (see Bossard 1916, Volume 5, p.9-16).

[8]See for example Du Boff (1967) on the crucial differences between mechanical and electrical power generation, transmission and use.

[9]In 1901, the longest transmission line in Switzerland was only 35km, however the maximum transmission distance doubled every 3-4 years to 72km in 1904 and 135km by 1908 (see Department des Inneren 1891-1920). The same geographical features to some extent remained relevant for electricity generation despite embankment dams requiring different geographical features starting to become the main source of electricity from 1914, see Figure B.4 and Bossard (1916). Importantly, I'm able to directly observe any further extension of local electricity generation that occurred after the initial 20 years to distinguish this effect from the initial adoption of electricity.

Figure 1: Electricity generation in 1900 and potential waterpower plants



Notes: The figure depicts potential and actual electricity generation across 1900 Switzerland. Colored areas depict the amount of actual electricity generation in a district by 1900. Black points represent all potential locations for waterpower plants at the time. The shape of the point corresponds to kW generation (historical groupings in HP=0.75kW). Both measures are based on a survey of existing and potential waterpower plants conducted by a commission of Swiss engineers at the time, which was instructed to identify the maximum waterpower potential across the whole of Switzerland (Bossard 1916).

while industries associated with the provision of electricity provided a considerable boost to industrialization in the short-run, the effect on economic development in the long-run is nearly exclusively associated with the use of electricity. In particular, my partial equilibrium estimate for chemical industries, where electricity was a crucial input in novel production processes, suggests that more than 70% of the spatial distribution of chemical industries across Switzerland today can be explained by early electricity adoption at the end of the 19th century.

Why did a 20-year period of early exposure to electricity have such important consequences for economic development? My preferred explanation is that earlier exposure triggered the accumulation of human capital and further innovation. In turn, this is what led to the persistent divergence in economic development. I find evidence that in areas which adopted electricity early, local schoolchildren immediately experienced an improvement in educational outcomes at the upper-tail of knowledge, especially in maths and general knowledge. This is substantiated by evidence that both the number of dual education institutions[10] and students expanded more quickly in areas which adopted electric-

[10]The cooperation of employers and local governments was crucial in the provision of knowledge through the dual education system in the form of apprenticeships, industry- and technical-schools. These also

ity earlier. The increased local importance of education is also underlined by increased support in national referendums for more central government investment in education. Consequently, it is not surprising that those areas remain more innovative with a higher rate of patenting. In contrast, the use of electricity per worker no longer differed at least by 1929 between areas which adopted electricity early and those that did not.

My paper contributes to several strands of the literature. First, a number of papers have studied the spread of electrification and economic development in advanced countries in the first half of the 20th century (Kitchens 2014; Kitchens & Fishback 2015; Gaggl et al. 2019; Lewis & Severnini 2019; Leknes & Modalsli 2020).[11] The contribution of this paper is to study the early adoption of electricity at the end of the 19th century. Looking at this earlier phase of adoption is important as electricity has long been seen as one of the key technologies of the second industrial revolution (see Mokyr 1992), but, its impact through the majority of this period (1870-1914) has not been thoroughly analyzed. The period 1880-1900 is also particularly relevant as it reflects a time of experimentation, where the economic gains of using electricity might not have been as clear as later on.[12] My paper finds that the adoption of electricity immediately accelerated industrialization with the impact per kilowatt appearing to be considerably larger in magnitude than at later stages of adoption. Further, I distinguish the role of electricity generation and use. In particular, the use of electricity is crucial in determining where the chemical industry developed highlighting important linkages in the main sectors of growth during the second industrial revolution.

Second, my paper contributes to a literature emphasizing the role of technical change on the formation of knowledge. It provides insights on the important question on whether technical change can foster human capital formation (Cervellati & Sunde 2005; Galor & Moav 2006; Galor 2011; De Pleijt et al. 2018). This should be seen in the context of the switch from steam engines to electricity as a power source representing a crucial breakpoint in the process of industrialization, which even changed the layout of factories (Du Boff 1967). My paper shows that the introduction of electricity as a power source led to an immediate increase in human capital accumulation at the end of the 19th century.The differences that emerged persisted with early adopters of electricity continuing to exhibit higher levels of education and innovation today. I also provide evidence on the

increasingly focused on providing theoretical rather than practical knowledge in the late 19th century as technological change increased the demand for an evermore skilled workforce (Wettstein 1987).

[11] Three papers looking at more particular questions are worth mentioning here as well. Molinder et al. (2019) studies the effect of electrification on social conflict, Vidart (2020) focuses on female labor force participation and Fiszbein et al. (2020) on its impact through replacing other forms of power across industries. A vast literature looks at the contemporary effect of electrification in developing countries starting with Dinkelman (2011).

[12] Juhász et al. (2019) document for mechanized cotton spinning that the initial adoption of a new technology can be rather tumultuous .

corresponding change in education demand (support for eduction spending) and supply (number of schools and students) to complete the picture.

The main contribution of my paper is to understand how the early adoption of new technologies shapes the divergence in economic activity.[13] This literature has been mostly restricted to analysing developments across countries (see e.g. Comin & Hobijn 2010; Comin & Mestieri 2018).[14] A noteworthy exception is Franck & Galor (2019), who show that areas which had adopted more steam engines at the height of the industrial revolution fell behind in the long-run due to technological inertia. Also, Lewis & Severnini (2019) highlight that rural electrification in the US between 1930-1960 led to an expansion in the agricultural sector, but had little effect on the local non-agricultural economy apart from driving suburban expansion. These studies suggest that while there are short-run gains from the adoption of technology on economic development at the local level, the long-run gains across areas are rather elusive in advanced countries. Notably, these papers focus on studying technology adoption at very mature stages with this context potentially being completely different (especially rural electrification) from the effect of the pioneering adoption of a new technology. My paper finds strong evidence that there are large gains from the earlier adoption of new technologies even within advanced countries. Areas that adopted electricity early continued to be more industrialized and have higher incomes more than 100 years later. This is despite electricity adoption having differed across areas for only a short period of time (20 years) with their being no evidence that early electricity adoption is related to its use after this short period. Instead the main mechanism that explains the lasting effect appears to be increased human capital accumulation and innovation crucial for continued economic development (in line with unified growth theory, see Cervellati & Sunde 2005; Galor 2011).

The remainder of my paper is organized as follows. Section 2 provides a historical example. Section 3 describes the empirical strategy and data used in the analysis. Section 4 presents the results for the contemporaneous effect as well as the long-run outcomes. Section 5 discusses potential mechanisms. Finally, Section 6 concludes. This is complemented by the Appendix containing additional A) figures and tables, B) information on the data and C) historical context. Figures and tables in these Appendices are identified with the corresponding letter.

[13]This, of course, closely relates to the literature on persistence in the spatial distribution of economic activity starting with the seminal work by Davis & Weinstein (2002) showing how location fundamentals were crucial in determining economic activity across Japan with the pattern of economic activity being robust to large temporary shocks caused by conflicts. However, surprisingly little attention has been given in this literature to the role played by initial technology adoption due to local advantages and constraints in explaining the divergence in economic activity.

[14]These findings from the cross-country literature correspond well to the stylized facts presented in Figure A.1, which shows a drastic divergence in income growth per capita between Switzerland, which was till the 1900s the largest adopter of electricity in the world, and other countries after electricity started to be adopted. A similar, but slightly less pronounced, divergence is also observable for the US, the second largest adopter of electricity at the time.

2 Historical Example

This section underlines the main empirical findings using the historical example of the firm "Lonza" and the municipality of "Gampel". A more broad historical context providing information on electrification in Switzerland and economic developments at the time is provided for the interested reader in Appendix C.

Figure 2: Lonza waterpower plant and factory in Gampel

Notes: The pictures show the Lonza chemical factory including waterpower plant in front of Gampel municipality (left) and the Alps (right) at the start of the 20th century. The larger white buildings in the front on the left picture is one of the the turbine houses (Gampel I) with water entering through the pressure pipe crossing the river Lonza. The smaller white building is the distribution station. On the right picture the chemical factory is in the foreground. The right picture also shows the pressure pipe running down from the mountain side towards the turbine house (partly hidden behind smoke). The water intake is located further up hill at a favorable bend in the river Lonza (close to the location of turbine house Gampel II). The local area website (in German) provides a history of the waterpower plants including a map: www.goppenstein.info. Source: Library ETH Zürich

Many Swiss chemical firms established at the end of the 19th century initially required the availability of cheap electricity (see e.g. Lunge 1901).[15] One of them, Lonza, was founded in 1897 in the rural municipality of Gampel (population of 421 in 1880) with its own waterpower plant producing electricity to manufacture chemicals, in particular calcium carbide. Figure 2 depicts the factory, waterpower plant and municipality at the start of the 20th century. The production of calcium carbide was based on the process developed by the French chemist Henri Moissan in 1892, which required a large amount of energy. The copying of the scientific process should, however, not distract from the challenges of putting scientific know-how into economic practice, which took Lonza considerable tenacity and refining (Eschenmoser 1997). For the initial carbide production, Lonza operated two waterpower plants in Gampel with an average electricity generation of 1725kW and 3750kW built in 1898 and 1900 using the water provided by the Lonza

[15]For example, AIAG (aluminum and potassium chlorate), Ciba (chlorine and sodium hydroxide), Compangie Electrique du Phosphor (phosphor), La Volta (sodium chloride), Lonza (calcium carbide), and Societe de Electrochemie (chlorate). Detailed examples of the emergence of these firms are for example provided in Kaufmann (1965) for the Canton of Wallis.

river (see Bossard 1916).[16] This indeed was the first larger industrial plant in the Canton of Wallis (Kaufmann 1965).

Lonza quickly outgrew Gampel in the following years and opened an additional production site in the neighboring municipality of Visp (11.9km away) in 1909 extending production to synthetic fertilizers, vitamins, acids, chemical intermediates and additives (Eschenmoser 1997).[17] Today Lonza is the 7th largest chemical company in Switzerland (48th overall) with a revenue of 5.5 billion CHF and 14,500 employees across 100 sites in 18 countries. The abundant availability of electricity (supplied also to others by firms like Lonza) and the emergence of large industrial firms sparked the broader growth of highly specialized small and medium sized industries in the area (see Kaufmann 1965, p.48). Most remarkably, even tough its Lonza plant closed in 1964, Gampel still boasts an extremely industrialized and high-skilled workforce with 4.7% being technical professionals or scientists in 2008 (see Bundesamt für Statistik 1860-2011).

An increased emphasis on education and innovativeness after electricity arrived appears to play a crucial role in this persistent economic success. The emergence of Lonza, and the chemical industry more generally, created new educational opportunities as well as demand for it (see e.g. Homburg et al. 1998; HLS 2020 "Chemie"). An example of this is Paul Hermann Müller, who after dropping out of secondary school in his home town due to bad grades joined Lonza as an assistant chemist in their industrial laboratory. There he acquired a wealth of practical knowledge which has been remarked upon throughout his career (NobelPrize.org 2020). Finishing his educational apprenticeship combined with an additional year in school allowed him to enter Basel University, receiving a Doctorate in 1925, and returning to work in the private sector afterwards. In 1948 he received the Nobel prize in medicine for his work on the synthesis of DDT, an important chemical compound in the eradication of malaria across the world.

Not just Lonza, but also the municipality of Gampel, was crucial in the formation of local human capital. For example, the Gampel council established the first secondary school in the area (Schnyder 1949, p.245). Highlighting how exceptional it was for a municipality at the time to foster this higher level of education is that surrounding municipalities were uninterested in supporting the establishment of the school despite 30% of the expenditure being subsidized by the Swiss state. The schools elite character is also highlighted by requiring school fees of students from other municipalities and an entrance

[16]The company Lonza takes its name from the 22km long rocky stream running also through Gampel characterized by its rapid current that provided excellent conditions for the generation of electricity (the part of the river viewable in Figure 2 is at the end shortly before joining into the upper-Rhone). Apart from this, the river Lonza has not been recorded to provide any noteworthy economic advantages or obstacles (Schnyder 1949, p.210).

[17]It should be highlighted that while these waterpower plants were initially build to supply energy to the production of chemicals, in 1914 all of them are listed as supplying electricity more broadly to the electricity grid and not just to the chemical industry Bossard (1916). Corresponding to this, chemical plants and electricity generation evolved into two separately run operations.

exam. This emphasis on education is not surprising considering a proverbial pioneering spirit based on science was observable in Gampel with several new production processes developed and patents recorded (Eschenmoser 1997).[18] In turn, this high level of human capital and innovativeness was likely crucial for Gampel's continued economic success even after the Lonza plant closed.

Importantly, Gampel is not just an exception. Section 4 will show that this local success story initiated by the luck of being early exposed to electricity led to economic development and human capital accumulation all across Switzerland.

3 Empirical Strategy

This section describes the empirical strategy and briefly summarizes the main data used. Additional detail on the data is provided in Appendix B.

3.1 Methodology

To answer the question of how the early adoption of new technologies shapes economic development, I explore the empirical relationship between the district-level early adoption of electricity at the end of the 19th century and indicators of development from 1860 up to today.

Swiss districts ("Bezirke"), the administrative level below the Cantons, provide the preferred unit of observation to evaluate this empirically as they are large enough so that the required historic information is available, but small enough to provide sufficient variation across Switzerland. These units of observation reflect distinct local labor markets at least up to the middle of the 20th century.[19] The 178 districts in my sample also provide a consistent unit of observation from 1860 till today.

I construct a measure of district-level electricity adoption between 1880-1900 as follows:

$$\Delta E_{d,1900-1880} = \frac{W_{d,1900} - W_{d,1880}}{N_{d,1880}} \tag{1}$$

where W is the electricity generated and N is the population of district d. Accordingly, the measure $\Delta E_{d,1900-1880}$ captures change in electricity adoption in kW (kilowatt) per

[18]A search for Gampel in the database of the European Patent Office finds 164 patents by 1937. A considerable amount for such a small municipality and Switzerland having introduced a comprehensive patenting law only by 1907.

[19]The development of the railroad and tram networks in Switzerland in the late 19th and early 20th century mainly improved the transport of goods and short-distance passenger traffic (see "Verkehr" in HLS 2020). A sizable geographic distinction between place of living and work only emerged with the building of motorways and mass motorization beginning in the 1950s. To better account for this, I use employment data based on the location of the workplace after 1955, rather than residence (the only measure available initially).

1880 person in each district between 1880 and 1900.[20] Population is kept constant to avoid any confounding effect from population changes due to electricity adoption. Crucially, electricity due to technological constraints was not yet supplied over long distances. Accordingly, this measure of electricity adoption captures both the effect of local generation and use of electricity in a district. Another key aspect is that this electricity adoption in Switzerland was exclusively based on waterpower (see Figure B.1).

I estimate the following equation to capture the contemporaneous effect of the adoption of electricity on measures of economic development:

$$\Delta DEV_{d,1900-1880} = \beta \Delta E_{d,1900-1880} + \gamma' X_{d,1880} + \epsilon_d \tag{2}$$

where $\Delta DEV_{d,1900-1880}$ denotes the respective measure of economic development with d representing district and 1900-1880 the time-period. I use alternative outcomes, but a particular focus is placed on the structural transformation from agriculture into manufacturing and service employment. This represents a crucial measure of economic development as historically areas became rich through labor reallocating from agriculture into modern activities with higher productivity and productivity growth (see e.g. Kuznets 1973). $X_{d,1880}$ are controls observed at the beginning of the period capturing differences across districts in 1880 that might influence the adoption of electricity as well as future economic development, and ϵ_d is the error term.

An obvious concern with a causal interpretation of the role of electricity in Equation 2 is that the decision to build a power-plant is affected by unobservable demand- and supply-side consideration due to economic development. On the one hand, economic development potentially creates an upward bias through increasing local demand for electricity. On the other hand, economic development potentially creates a downward bias by complicating the building or extension of waterpower plants for electricity generation. In particular, already awarded water-concessions (usually lasting at least 50 years) as well as unclear ownership in densely populated areas are noted in Bossard (1916) as considerable obstacles for the exploitation of the full waterpower potential for electricity generation.[21]

To address the potential endogeneity of electricity adoption, I use the following first-stage regression:

$$\Delta E_{d,1900-1880} = \varphi \log P_d + \phi' X_{d,1880} + \mu_d \tag{3}$$

[20] The measure is in kW rather than kWh as it reflects the average power that the installed turbines in a waterpower plant can generate throughout the year conditional on the available water-flows. Note that the first waterpower plant in Switzerland build in St. Moritz in 1879 had only a 7kW turbine, which is below the recording threshold in Bossard (1916) of 15kW, so that in effect $W_{d,1880}$=0.

[21] The city of Basel is an excellent example for this issue. Despite the city rapidly industrializing and having a large local waterpower potential, only a number of small waterpower plants (mostly pre-electricity) had been build due to individual ownership of water concessions preventing the building of a large waterpower plant for electricity generation.

where the increase in the generation of electricity between 1880 and 1900 is instrumented by the log potential for energy generated from waterpower per person in 1880, denoted $\log P_d$.[22] The waterpower potential is based on a detailed plan — devised by engineers at the time — of all existing and potential waterpower plants and the energy they could generate (see Bossard 1916). The relevance of the waterpower potential for actual electricity adoption by 1900 is clearly observable in Figure 1. Importantly, the aim for the calculation of the waterpower potential is explicitly stated as aiming to optimally exploit waterpower for energy generation using the current level of technology disregarding i) any non-geographical obstructions that could inhibit the building of waterpower plants, and ii) any considerations for the economic viability of waterpower plants (see Bossard 1916, Volume 5, p.9-16). This explicitly rules out that waterpower potential is affected by the before mentioned demand- and supply-side consideration due to economic development.

Another crucial point is that the potential to generate electricity is as good as randomly assigned across areas with regards to ex-ante economic development. First, while districts with and without electricity generation in 1900 differ in terms of economic development already by 1880, there are no observable differences between districts with and without waterpower potential for electricity generation by 1880 (see Table 1).[23] Next, Table 2 looks at whether potential electricity generation is also as good as random along the intensive margin. Panel A illustrates the relationship between potential kW per km^2 and important characteristics of economic development in 1880. This measures whether the distribution of waterpower potential is as good as randomly located across the area of Switzerland with regard to pre-existing economic development, i.e. each area has the same likelihood for waterpower potential independent of the economic development in the area by 1880. This appears to be the case as there is no significant relationship between potential kW per km^2 and population density, agricultural, manufacturing or services employment share across districts, both with and without controlling for major geographic differences. Panel B considers to which degree economic development and log potential kW per person are unrelated. While it initially appears that the potential per person is highest in the least developed areas, this relationship emerges mechanically. Accordingly, it vanishes as soon as one controls for major geographic differences that are crucial for persistent differences in

[22] For simplicity I refer to the transformation as the log while the exact transformation used is the inverse hyperbolic sine which closely relates to a log-transformation in its functional form, i.e. $\log(x+((x^2+1)^{0.5}))$, but also allows 0 values to be transformed. I adopt a log transformation to capture the decreasing returns from electricity potential. Indeed as can be seen in Figure 1 some districts had a potential exceeding Switzerland's 1900 total electricity adoption. Results are robust to using potential for energy produced from waterpower per person as the instrument with results displaying slightly wider confidence intervals.

[23] The potential electricity generation across districts only appears associated with some major geographical differences, but not population density, agricultural, manufacturing or services employment share. Districts are more likely to be situated in the east of Switzerland and have a 246m higher average altitude (with 960m being the average altitude across districts).

Table 1: Balance checks actual and potential electricity adoption

	Control		Treatment			
Variable	Mean	N	Mean	N	Diff	P value
A1. Difference between no-electricity vs. electricity generation						
Share agricultural employment (1880)	0.51	93	0.47	85	0.041	
Share manufacturing employment (1880)	0.37	93	0.38	85	-0.009	
Share services employment (1880)	0.12	93	0.15	85	-0.032	* * *
Population density (1880)	0.11	93	0.15	85	-0.038	
A2. Difference between no-electricity vs. top 33% of electricty generation						
Share agricultural employment (1880)	0.51	93	0.46	60	0.058	*
Share manufacturing employment (1880)	0.37	93	0.38	60	-0.013	
Share services employment (1880)	0.12	93	0.16	60	-0.045	* * *
Population density (1880)	0.11	93	0.17	60	-0.060	
B1. Difference between no-potential vs. any electricity potential						
Share agricultural employment (1880)	0.53	29	0.49	149	0.041	
Share manufacturing employment (1880)	0.34	29	0.38	149	-0.047	
Share services employment (1880)	0.14	29	0.13	149	0.006	
Population density (1880)	0.10	29	0.14	149	-0.037	
B2. Difference between no-potential vs. top 33% of electricity potential						
Share agricultural employment (1880)	0.53	29	0.57	60	-0.044	
Share manufacturing employment (1880)	0.34	29	0.29	60	0.046	
Share services employment (1880)	0.14	29	0.14	60	-0.002	
Population density (1880)	0.10	29	0.09	60	0.005	

Notes: T-test between mean statistics for indicators of the level of development in 1880 across districts. Panel A compares the indicators across districts with electricity generation in 1900 (treatment) and those without electricity generation (control). Panel B compares the indicators across districts with potential waterpower (treatment) and without potential waterpower (control). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

population desity across Switzerland.[24] This provides considerable support for potential waterpower being as good as randomly distributed across districts with regards to initial economic development. Figure A.3 provides additional descriptive maps for electricity adoption, geography and economic development across Switzerland.

That the waterpower potential started to be relevant for economic development only through electricity is further supported by Figure 3. It shows in the left-panel (equivalent to the map presented in Figure 1), that the waterpower potential is a strong predictor of the electricity produced across districts by 1900. While in the right-panel it shows, that the waterpower potential is not relevant for the energy generated from watermills by 1880.

[24]Note that if potential to generate electricity is as good as randomly distributed across Switzerland with regards to geography and there are differences in population density across areas, that in a mechanical way more densely populated areas will have a lower potential per person. This can be illustrated in the following way, consider Switzerland was divided into 1x1km grid cells and each cell would have the same likelihood to be able to generate electricity independent of anything else. Even if potential electricity is random, more densely populated grid cells would have a lower per capita potential for electricity generation on average. Figure A.2 illustrates this relationship. However, conditioning for geographic factors that determine population density in the very long-run, e.g. altitude, the relationship across cells should again be as good as random.

Table 2: Evidence for randomness of potential to generate electricity

	Population density 1880		Share employment 1880 in: Agriculture		Manufacturing		Services	
A. Geography	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Potential kW per km^2	0.004	0.004	-5e^{-4}	1e^{-5}	2e^{-4}	-3e^{-4}	2e^{-4}	2e^{-4}
	(0.002)	(0.002)	(5e^{-4})	(0.001)	(3e^{-4})	(4e^{-4})	(2e^{-4})	(2e^{-4})
Altitude (km)		-0.098***		0.082		-0.064		-0.018
		(0.032)		(0.061)		(0.054)		(0.024)
Longitude		0.034		-0.011		0.005		0.006
		(0.033)		(0.029)		(0.025)		(0.007)
Latitude		-0.026		-0.148*		0.180**		-0.032
		(0.056)		(0.079)		(0.075)		(0.019)
B. Population								
Log potential per person	-0.056**	-0.019	0.102**	0.060	-0.101**	-0.061	-0.001	0.000
	(0.020)	(0.022)	(0.044)	(0.043)	(0.037)	(0.037)	(0.011)	(0.008)
Altitude (km)		-0.108***		0.056		-0.037		-0.019
		(0.033)		(0.062)		(0.057)		(0.024)
Longitude		0.036		-0.016		0.010		0.006
		(0.031)		(0.027)		(0.024)		(0.006)
Latitude		0.035		-0.148*		0.176**		-0.027
		(0.046)		(0.075)		(0.071)		(0.018)
N	178	178	178	178	178	178	178	178

Notes: Panel A presents whether the potential to generate electricity with regards to area size is correlated with economic development by 1880. Panel B does the same for the log potential per person. Controls for geographical factors (altitude, longitude, latitude) account for persistent differences in population desity across Switzerland. Robust standard errors in parentheses are clustered at the cantonal level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The later might appear surprising at first, however it reflects that the equipment used for mechanical power generation and transmission, i.e. wheels, shafts, gears, and belts, were not able to transmit the considerable amounts of energy that waterpower could provide.Accordingly,the technologies available before electricity were unable to exploit the potential waterpower measured in Bossard (1916). This suggests that the specific geographic features relevant for electricity generation were otherwise economically irrelevant, including for power generation in other ways, supporting the validity of the exclusion restriction. To even further alleviate any concerns, I will later also present estimates based on Equation 2 for 1860-1870 and 1870-1880, which show that the early adoption of electricity 1880-1900 is unable to predict any economic development in this pre-period.

Next I study whether the contemporaneous effect persists in the long run: I analyze in separate regressions the effect of the early adoption of electricity on economic development. The equation below outlines the expanded empirical strategy:

$$\Delta DEV_{d,t-1880} = \beta_t \Delta E_{d,1900-1880} + \gamma_t' X_{d,1880} + \gamma_t \Delta E_{d,t-1900} + \epsilon_d \tag{4}$$

$$where\ t = 1900, 1920, 1941, 1955, 1965, 1975, 1985, 2011$$

$\Delta DEV_{d,t-1880}$ is the dependent variable of interest, where t now denotes the respective end point of the time period. Each specification being estimated individually means that the effect of the early adoption of electricity and the initial controls can vary over-time, which is denoted by the subscript t on the coefficients.[25] In addition to the previous specification I also control for extensions in electricity generation from waterpower that occur after 1900 ($\Delta E_{d,t-1900}$). While local supply of electricity in the long-run is independent of these new waterpower plants due to the development of long-distance transmission grids, this variable accounts for the potential correlation between the instrument and the construction and operation of waterpower plants that occurs after 1900 (see Table B.2). The emergence of the long-distance transmission also meant that the later placement of new waterpower plants was based exclusively on where in Switzerland it was most efficient to generate electricity, independent of local demand for electricity (see Eidgenössische Amt für Wasserwirtschaft 1928-2018). So that, $\Delta E_{d,t-1900}$ is not affected by economic development $\Delta DEV_{d,t-1880}$ caused by $\Delta E_{d,1900-1880}$ avoiding a bad control problem.[26]

Consequently, the historical context of electricity adoption and the instrumental variable strategy provide an unique empirical setting. In which the adoption of a new technology was plausibly randomly assigned to areas for only a short period of time, while the technologies impact on economic development can be traced for more than 100 years.

3.2 Data

Information on electricity generation across Switzerland between 1880-1900 comes from "The waterpower of Switzerland in 1914" (see Bossard 1916).[27] This source provides information on building and extension dates, energy generation, type of energy, and location for all waterpower plants in Switzerland with a generation capacity of more than 15kW (≈20 horsepower). The same source also provides information on location and energy generation for all potential waterpower plants that could be build across Switzerland to maximize electricity generation by 1900.[28] From this, I calculated the electricity generation and potential electricity generation at the district level. Panel A in Table 3, which presents summary statistics for the main variables, highlights that the average electricity

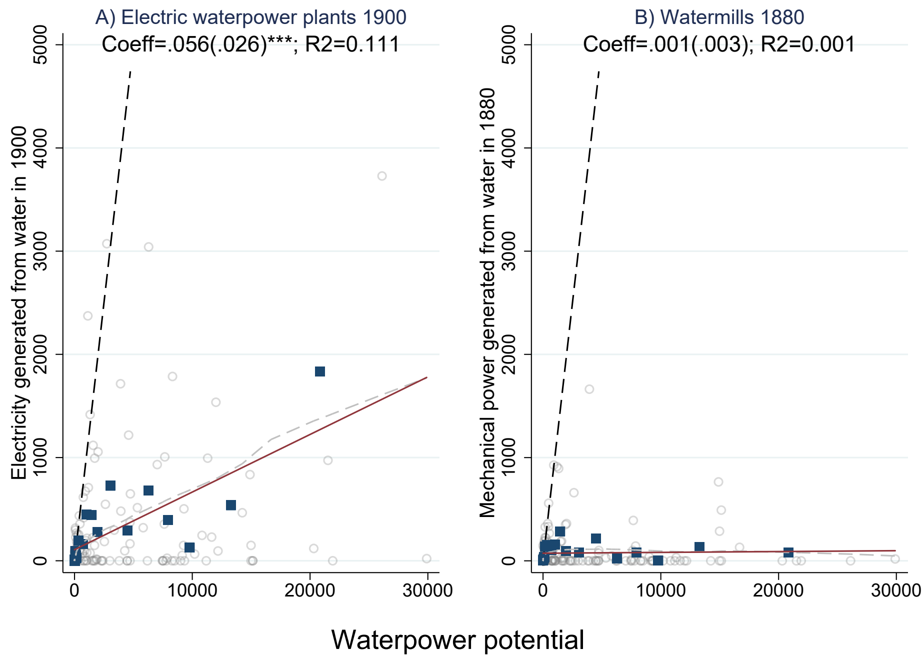
[25]This is crucial as the effect of initial characteristics is unlikely to be constant over time. Apart from $\Delta E_{d,t-1900}$, the estimated coefficient β_t would be closely related to an event-study specification, where the observations are pooled and each included variable is interacted with time fixed effects.

[26]This interpretation is supported by later results showing that not controlling for $\Delta E_{d,t-1900}$ slightly overestimates the instrumented impact of $\Delta E_{d,1900-1880}$ and that already in the period 1900-20 the effect of $\Delta E_{d,t-1900}$ is exclusively associated with employment in electricity generation and distribution, but no other manufacturing sectors.

[27]This publication (Bossard 1916) and the later comparable publications (Eidgenössische Amt für Wasserwirtschaft 1928-2018) are official statistics published by the Swiss ministry of the interior, which tasked a group of mainly government engineers with the collection, calculation and composition of the reports, tables, and figures assessing the actual and potential waterpower of Switzerland.

[28]Bossard (1916) also reports potential waterpower plants that require the building of embankment dams (see Figure B.4 & B.6). However, as these only started to be constructed during the 20th century they are not included in my measure for potential electricity generation.

Figure 3: Electric- versus mechanical-power generated from potential



Notes: The figure illustrate the relationship between the total waterpower potential in kW of a district and A) electricity generation from waterpower by 1900 and B) the energy generated by watermills using exclusively mechanical power transmission by 1880 across districts. X-axis presents potential kW from waterpower. Y-axis presents actual kW of energy generated. Blue squares represent the binned observations with the solid red line being the linear fit. Hollow gray dots in the background correspond to the underlying observations. The dashed gray line depicts the locally weighted fit. The blacked dashed line provides a 45-degree line of full exploitation of the potential. Some districts actual electricity generation is slightly above the 45-degree line due to variation in the water level throughout the year, i.e. turbines have been installed that operate at less than full capacity when the water level is low. Geneva with 9900kW generation and 16785kW potential lays outside of the depicted range in A). N=178 in 20 bins.

adoption 1880-1900 was 0.02kW per person. I augment this information on the number of waterpower plants and electricity produced for the period after 1914 with later publications of the "Statistics of waterpower plants in Switzerland" (see Eidgenössische Amt für Wasserwirtschaft 1928-2018), which extends the information on waterpower plants up to 2018. More detailed information on the electricity data is provided in Appendix B.1.

To study the effect on economic development I first collected information on structural change (employment across agriculture, manufacturing and services) from the Swiss Censuses focusing on the years 1860, 1870, 1880, 1900, 1920, 1941, 1955, 1965, 1975, 1985 and 2011 (see Bundesamt für Statistik 1860-2011).[29] These provide information on employment of individuals for the whole of the Swiss population aggregated at the district level. Panel B-D in Table 3 highlights that by 1880 Switzerland was still a mainly agricultural

[29]These sources are the official Census statistics aggregated and reported at the time by the statistical department of the Swiss ministry of the interior based on the 100% population censuses that had been conducted.

Table 3: Summary statistics

	Mean	SD	10th	90th	N
Panel A. Electricity adoption 1880-1900					
Δ Electricity pp 1880-1900	0.02	0.05	0.00	0.04	178
Log waterpower potential pp	0.23	0.40	0.00	0.79	178
Panel B. Agricultural employment share 1880-2011					
Share agricultural employment 1880	0.49	0.20	0.23	0.73	178
Change agricultural share 1880-1900	-0.07	0.07	-0.13	-0.00	178
Change agricultural share 1880-1920	-0.11	0.08	-0.22	-0.01	178
Change agricultural share 1880-1955	-0.17	0.13	-0.33	-0.00	178
Change agricultural share 1880-2011	-0.42	0.17	-0.64	-0.18	178
Panel C. Manufacturing employment share 1880-2011					
Share manufacturing employment 1880	0.37	0.17	0.16	0.63	178
Change manufacturing share 1880-1900	0.05	0.05	-0.01	0.11	178
Change manufacturing share 1880-1920	0.05	0.07	-0.03	0.14	178
Change manufacturing share 1880-1955	0.09	0.13	-0.05	0.24	178
Change manufacturing share 1880-2011	-0.08	0.17	-0.32	0.12	178
Panel D. Services employment share 1880-2011					
Share services employment 1880	0.13	0.07	0.07	0.22	178
Change services share 1880-1900	0.02	0.04	-0.00	0.05	178
Change services share 1880-1920	0.06	0.05	0.02	0.12	178
Change services share 1880-1955	0.08	0.08	0.01	0.17	178
Change services share 1880-2011	0.51	0.10	0.39	0.63	178

Notes: The table reports summary statistics for the main explanatory and dependent variables. The columns report mean, standard deviation, 10th and 90th percentile and number of observations.

economy, but that there was rapid structural change after 1880 with employment first transitioning from agriculture to manufacturing and then to services.

From the Swiss Censuses, I also collected more detailed information on employment in different manufacturing industries for the years 1860, 1880, 1900, 1920 and 1975, identifying seven consistent groups out of the categories reported in the census: “Electricity generation”, “Construction, wood & stone products”, “Chemicals”, “Textiles & apparel”, “Food products”, “Metal, machinery & watches”, and “Other”.[30] The category “Other” mainly comprises employment in mining, paper and typography. This additional breakdown by industries allows me to distinguish to which extend the effect of electricity adoption on manufacturing was due to electricity generation itself or rather due to the use of electricity. Additional information on the Census Data is provided in Appendix B.2.

[30]Construction is included within manufacturing because even in the disaggregated historical information for 1880-1920 the construction of buildings is reported in one category together with the production of materials predominantly used for construction (wood and stone products). Accordingly, I follow the historic classification and count construction within manufacturing throughout.

The remaining data sources used to evaluate the potential mechanisms and construct control variables are described in Appendix B.3.

4 Results

This section analyses the effect of early electricity adoption on economic development across districts in Switzerland. First, Section 4.1 shows that early electricity adoption led to structural change at the end of the 19th century. Second, Section 4.2 shows that the effect of early exposure to electricity persisted over time, despite the fact that the extension of the electricity grid allowed access to the new technology regardless of location. In Section 4.3 I show that early adoption of electricity had significant short-run effects on industries associated with the generation of electricity, but the long-run effect is mostly due to industries which benefited from the earlier use of electricity.

4.1 Effect of electricity in the late 19th century

I start in Table 4 Panel A by analyzing the effect of the adoption of electricity between 1880-1900 on the change in the share of employment in agriculture 1880-1900.[31] This corresponds to the estimation strategy outlined in Equation 2. Column 1 highlights that a higher electricity adoption is associated with a substantial decrease in agricultural employment across districts. The next columns introduces a number of initial confounding factors that might drive both the adoption of electricity and economic development between 1880-1900 across districts.

A first concern is that electricity generation might be correlated with major geographic differences across Switzerland, which might also influence economic development. To account for this, I add altitude, longitude and latitude as controls in the second column. Indeed a higher altitude is consistently associated with less transition out of agriculture, while the effect of longitude and latitude is less clear.

A second concern is that electricity adoption is driven by the initial level of economic development, which might also be related to future economic development. In column 3, I control for the 1880 agricultural employment share, population density and average educational test scores. No clear pattern of convergence nor divergence in economic development is observable across districts.

A third concern is the pre-existing use of mechanical waterpower through watermills, which were the dominant source of power in Switzerland up to the middle of the 19th century until the steam engine overtook it in importance. The previous use of waterpower

[31] Standard errors are clustered at the cantonal level due to their administrative importance within Switzerland. Similarly, sized standard errors are obtained clustering for spatially correlated error terms with a 35km kernel (the longest transmission distance by 1900).

through watermills might also influence electricity generation after 1880, so that industrialization due to the operation of watermills could be falsely attributed to the adoption of electricity after 1880. Column 4 controls for the mechanical energy generated per person in watermills by 1880. Indeed, the use of mechanical waterpower by 1880 is associated with a greater decline in agricultural employment 1880-1900.

A final concern is that there are region-specific unobservables in economic development which are correlated with electricity adoption. Column 5 accounts for different trends in economic development across the seven major economic regions (NUTS-2) in Switzerland.Across all specifications the main coefficient of interest remains similar in size. I choose column 5 as my baseline specification. The -0.291 coefficient in column 5 implies that the share of agricultural employment in a district with a one standard deviation higher exposure to electricity decreased by 1.5 percentage points more than in a comparable district.[32]

Appendix Table A.1 highlights that the coefficient is also robust to accounting for a vast set of other human characteristics that have been highlighted to be of importance for economic development: upper-tail human capital,religion, culture and institutions. As well as controlling for a vast set of additional geographic characteristics (Canton, cropland, presence of major rivers, average water-flow of any type of river (including small creeks), bioregions, ruggedness).[33]

Panel B of Table 4 uses the instrumental variable strategy outlined in Section 3 to account for unobservable factors not accounted for so far. The estimated effect can be interpreted as the local average treatment effect of being assigned the option to generate a certain amount of electricity from waterpower. The first-stage coefficient is highly relevant across all specifications and suggests that a 40% (one standard deviation) higher potential to generate electricity per person leads to a 0.02kW per person higher electricity adoption by 1900. Accordingly, this first-stage provides exogenous variation in the adoption of electricity independent of economic considerations.

The magnitude of the IV coefficient for the effect of electricity adoption roughly doubles in size compared to the OLS regressions across all columns. A plausible explanation for this is the presence of unobserved constraints in the use of waterpower for electricity generation in areas developing more rapidly. The key issue here appears to have been that water-concessions had been allocated for other purposes and were fragmented in areas undergoing industrialization and that legal ownership-rights were often unclear and difficult

[32] The coefficient of -0.291 indicates that a 1kW increase in generated electricity per person (a standard deviation is 0.05kW, see Table 3) predicts a decrease in the employment share in agriculture of 29.1 percentage points.

[33] These measures are based on modern data due to no historical information being available. Accordingly, their measurement might be affected by the building of waterpower plants and later economic development themselves making them potentially bad controls.

Table 4: Effect of electricity on structural change 1880-1900

A. Agriculture (OLS)	(1)	(2)	(3)	(4)	(5)
Δ Electricity pp 1880-1900	-0.291***	-0.315***	-0.321***	-0.314***	-0.291***
	(0.041)	(0.050)	(0.057)	(0.057)	(0.042)
	[0.050]	[0.046]	[0.052]	[0.051]	[0.037]
Altitude (km)		0.037**	0.045**	0.044**	0.061**
		(0.014)	(0.020)	(0.020)	(0.028)
Longitude		-0.004	-0.006	-0.005	-0.049***
		(0.004)	(0.005)	(0.005)	(0.014)
Latitude		0.047***	0.043***	0.045***	0.040
		(0.014)	(0.013)	(0.013)	(0.032)
Share agricultural employment 1880			-0.031	-0.037+	-0.020
			(0.028)	(0.027)	(0.033)
Population density 1880			0.003	0.001	0.006
			(0.007)	(0.007)	(0.006)
Average educ. grade 1880			-0.014	-0.012	-0.013
			(0.021)	(0.021)	(0.021)
Watermills 1880				-0.667+	-0.739*
				(0.413)	(0.399)
Region FE	No	No	No	No	Yes
adj. R^2	0.048	0.089	0.090	0.097	0.131
N	178	178	178	178	178
B. Agriculture (IV)					
Δ Electricity pp 1880-1900	-0.500**	-0.756***	-0.731***	-0.734***	-0.625***
	(0.238)	(0.260)	(0.251)	(0.249)	(0.212)
	[0.264]	[0.300]	[0.269]	[0.268]	[0.268]
	{-1.0,-0.1}	{-1.3,-0.3}	{-1.2,-0.3}	{-1.2,-0.3}	{-1.1,-0.2}
First stage estimate	0.048***	0.051***	0.054***	0.054***	0.057***
	(0.008)	(0.011)	(0.012)	(0.012)	(0.014)
F-stat (1st stage)	36.56	20.51	19.96	19.98	16.66
Reduced form estimate	-0.024*	-0.038***	-0.039***	-0.039***	-0.036**
	(0.012)	(0.010)	(0.010)	(0.010)	(0.013)
C. Manufacturing (IV)					
Δ Electricity pp 1880-1900	0.417*	0.536**	0.570**	0.573**	0.532**
	(0.241)	(0.271)	(0.282)	(0.279)	(0.262)
	[0.226]	[0.301]	[0.296]	[0.294]	[0.305]
D. Services (IV)					
Δ Electricity pp 1880-1900	0.083	0.220+	0.161	0.162	0.093
	(0.206)	(0.135)	(0.151)	(0.152)	(0.162)
	[0.213]	[0.112]	[0.144]	[0.144]	[0.181]

Notes: The dependent variable is the change in the share of employment in agriculture between 1880 and 1900 across districts. Panel A presents the OLS-estimates for the effect of electricity adoption per person between 1880-1900. Panel B presents the corresponding IV-estimates for electricity adoption per person between 1880-1900 using log waterpower potential per person as instrument. Panel C and D present the IV-estimates using the change in manufacturing and services employment share as dependent variable, respectively. Robust standard errors in parentheses are clustered at the cantonal level. Conley standard errors accounting for spatial correlation in square brackets and Anderson & Rubin weak instrument robust 90%-confidence intervals in curly brackets. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

to resolve, when potentially large economic gains existed (see Bossard 1916, Volume 4, p.7-8; 15-17).[34]

The coefficient (-0.625) in column 5, obtained using the IV strategy, implies that a district which had a one standard deviation higher exposure to electricity experienced a 3.1 percentage points decline in the share of agricultural employment.[35] A way to appreciate the overall magnitude of the effect is to work out the contribution of electricity to the overall change in agricultural employment between 1880 and 1900. Since average adoption of electricity was 0.02kW per person (see Table 3), the coefficient implies a decrease in the agricultural employment share of 1.3 percentage points between 1880 and 1900 in the average district. The average decline in agricultural employment over this period was 6.6 percentage points, so that this suggests 20% of the decline in agricultural employment between 1880 and 1900 was due to the adoption of electricity. This partial equilibrium estimate, of course, does not take into account any losses of industrial employment or positive spillovers in other districts due to the adoption of electricity.

Panel C and D of Table 4 show that the shift out of agricultural employment mainly increases manufacturing employment and there is little effect on employment in services. The coefficient for the manufacturing share (column 5) suggests that a one standard deviation higher exposure to electricity increased manufacturing employment by 2.7 percentage points. The average increase in manufacturing employment over this period was 4.7 percentage points. This suggests that 23% of the increase in manufacturing employment in Switzerland between 1880 and 1900 was due to the adoption of electricity.

The adoption of electricity did not just lead to changes in the share of employment across sectors, but also increased the employment growth rate. Table 5 Panel A shows that the adoption of electricity led to overall employment growth and employment growth in manufacturing, while employment in agriculture declined. Notably, Panel B looking at the growth in the population born in the respective municipality, Canton, Switzerland or a foreign country does not change due to the adoption of electricity. This, importantly, implies that structural transformation was driven by the local population changing from agricultural to manufacturing occupations.[36] This rules out that the observed structural change simply reflects internal migration and the reallocation of employment to where

[34]Figure A.4 provides suggestive evidence for this. It highlights that areas which exploit a large share of their potential have a smaller marginal effect from electricity adoption compared to areas exploiting a small share of their potential. This is inconsistent with local demand for electricity driving adoption. Instead the observed pattern is consistent with areas that have the largest gains from electricity adoption having more constraints in actually adopting it.

[35]Considering the standard errors, the effect range lies between -4.2 and -2.1 percentage points.

[36]Male labor force participation in 1880 Switzerland was nearly 100% amongst working age males. However, the census records about 3% of men as unemployed (no occupation and relying on some sort of financial support) in 1880. Table A.4 highlights that the initial employment growth 1880-1900 was due to men finding employment, while later increases were likely due to increased female labor force participation (below 50% in 1880).

Table 5: Effect of electricity on employment and population growth

A. Employment	All (1)	Agriculture (2)	Manufacturing (3)	Services (4)
Δ Electricity pp 1880-1900	1.242***	-0.553***	2.527**	1.203+
	(0.456)	(0.180)	(1.255)	(0.839)
B. Population	Municipality (5)	Canton (6)	Swiss (7)	Foreign (8)
Δ Electricity pp 1880-1900	0.199	0.425	-1.381	3.264
	(0.282)	(0.516)	(2.604)	(2.986)
Controls	Yes	Yes	Yes	Yes
N	178	178	178	178

Notes: The dependent variable is the growth rate of employment and population between 1880 and 1900 as specified in the column header. The presented IV-estimates for the effect of electricity adoption per person between 1880-1900 uses log waterpower potential per person as instrument. Column 1-4 present the effect on total, agricultural, manufacturing and services employment growth. Column 5-8 present the effect on population growth of individuals originating from the municipality, from another municipality inside the canton, from another canton in Switzerland and from outside Switzerland. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

energy was cheapest. Instead the local population clearly had to acquire the knowledge and skills required for the newly emerging manufacturing jobs.

The crucial assumption for the IV results to be valid requires that the potential to produce electricity from waterpower affects economic development only through electricity adoption. One way to test this is to study whether the instrumented adoption of electricity 1880-1900 is observed to have an effect on outcomes before electricity started to be adopted in the 1880s. I conduct this falsification exercise in Table A.2 by replacing my dependent variables with the change in employment shares between 1860-1880 in Panel A, 1860-1870 in Panel B and 1870-1880 in Panel C.[37] There is no evidence that districts experienced a different pattern of development before electricity started to be adopted in the 1880s (the insignificant coefficients even go in the reverses direction compared to the effect 1880-1900).

4.2 Lasting impact of early electricity adoption

I now turn to my second key question: whether the early adoption of electricity had a lasting impact on economic development. Figure 4 presents IV estimates, based on Equation 4, for the effect of early electricity adoption on structural change from 1880 up to today. Figure A.5 present the corresponding OLS estimates.[38]

[37]To be consistent I also change all initial controls for 1880 to 1860. Accordingly, I include the share of agricultural employment, population density, energy generated by watermills per person for 1860 instead of 1880 across district. No data for average education grade is available in 1860.

[38]The OLS estimates, similar to the IV results, suggest a persistent effect of early electricity adoption on structural transformation up to today. However, the OLS results suggest the lasting effect to be mostly

The first panel presents the coefficient for the effect of the change in electricity 1880-1900 on the agricultural employment share over time. Each coefficient represents a separate regression with the change in agricultural employment 1880 to point t in time as dependent variable (the coefficients up to 1900 correspond to the results discussed in Section 4.1). The coefficients suggest that the impact of early electricity adoption persisted despite electricity becoming universally available after 1900. The magnitude of the coefficient even increased till 1955. After 1955 the impact of early electricity adoption slowly starts to decline. However, the coefficient for the effect of electricity adoption 1880-1900 is still significant and of economic importance by 2011 as it suggests a 3.3 percentage points lower agricultural employment share for each standard deviation higher exposure to electricity 1880-1900. This suggests a considerable long-run effect of earlier exposure to electricity.

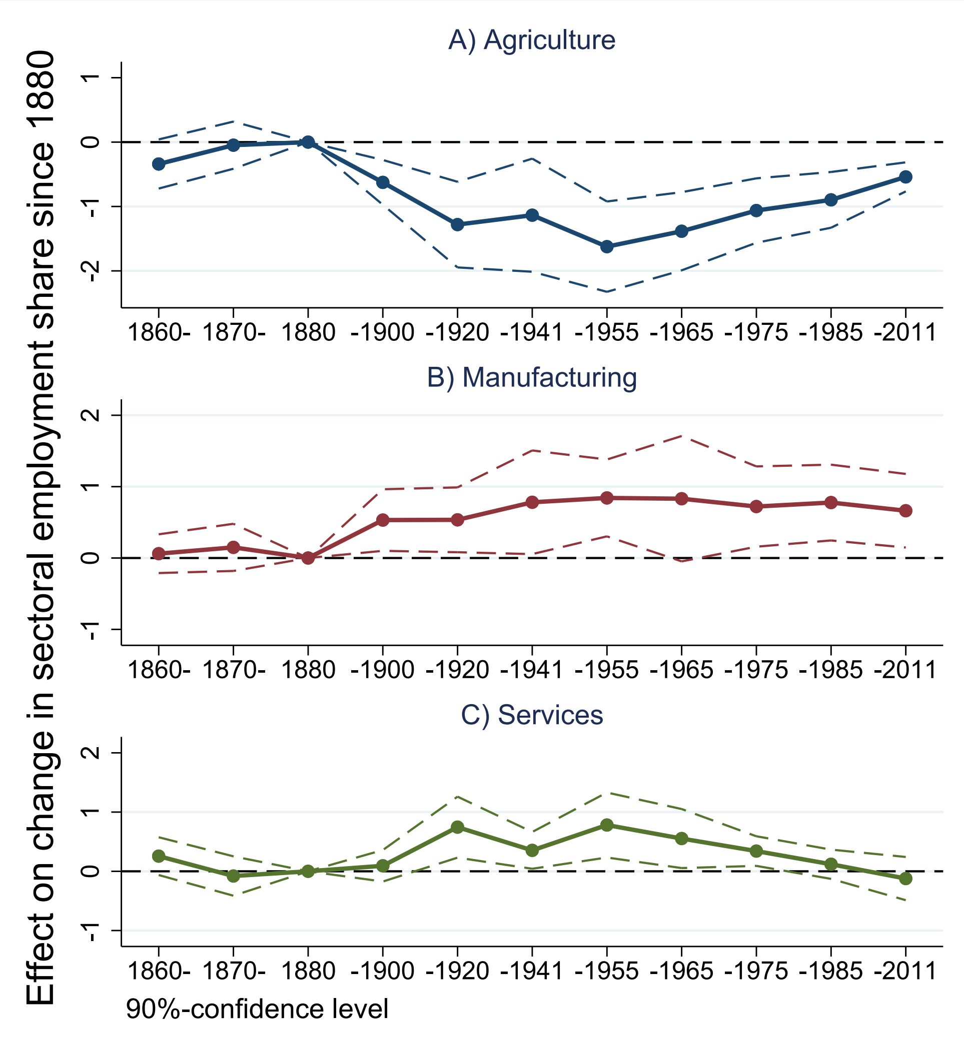
The second panel of Figure 4 shows the effect of early electricity adoption on the manufacturing employment share. The coefficients suggest that early electricity adoption contributed to the growth of manufacturing till the mid-20th century with the level remaining stable till 2011. To illustrate the economic importance, a district which had a one standard deviation higher increase in electricity between 1880-1900 had a 2.7, 3.9, 3.6, and 3.3 percentage point higher manufacturing employment share by 1920, 1941, 1975 and 2011, respectively. This illustrates that earlier exposure to electricity in the brief period 1880-1900 triggered a process of industrialization that reached its peak only several decades later and considerably contributed to different levels of industrialization across districts more than 100 years later.

The final panel of Figure 4 presents the effect on the service sector. Here, the coefficients suggest a mixed effect, while there is some indication of early electricity adoption having increased the service sector share of employment in some periods the effect varies greatly with regards to the specific time-period and by 2011 districts had converged again in the share of service employment.

In general, this pattern is also observed when looking at overall employment across sectors. Areas exposed earlier to electricity continued to experience significantly higher (lower) employment growth rates in manufacturing (agriculture) throughout the 20th century, and not just an contemporaneous increase to the level of industrialization (see Table A.3). Sectoral employment growth rates only converged in the late 20th century. Despite the employment share in services converging again in the second half of the 20th century between areas which adopted electricity early and those which adopted electricity later, no corresponding difference in service employment growth is observable after 1920. This seems to suggest that the convergence in the share of service employment in areas

due to the transition from agriculture to services as the effect on manufacturing vanishes in the 1940s-60s (a period of war disruptions and rapid economic transformation, see Figure B.7). The manufacturing convergence estimated during this disruptive period seems in line with the downward bias discussed.

Figure 4: Effect of early electricity adoption on structural change



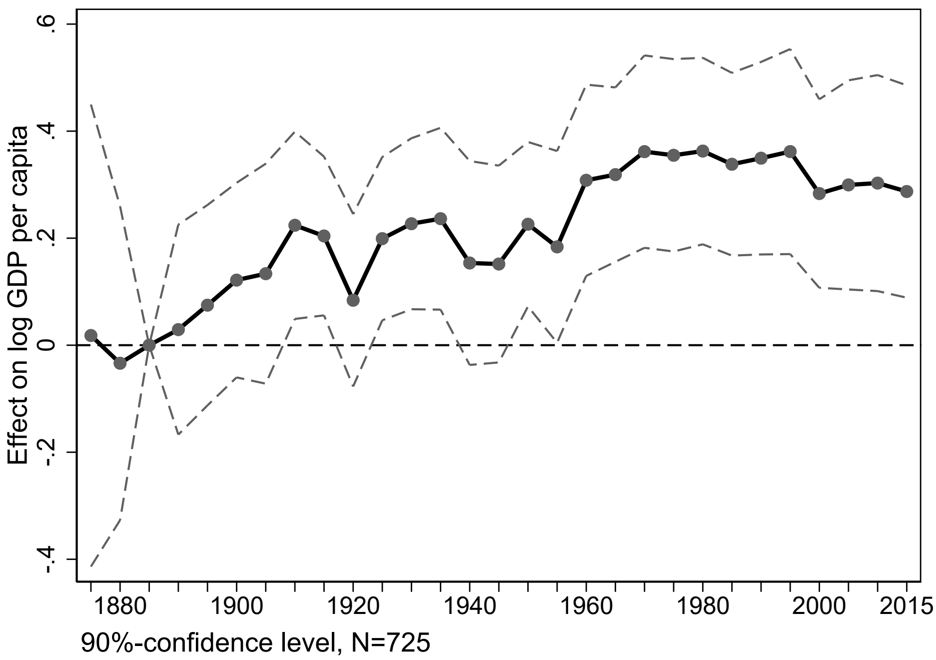
Notes: The figure presents the IV-estimates for the effect of early electricity adoption per person between 1880-1900 on the change in the employment share across sectors from 1880 to the specified year (reverse for pre-trend compared to Table A.2). The instrument used is log waterpower potential per person. Regressions include the full set of baseline controls and robust standard errors are clustered at the cantonal level. The pre-trend periods include initial controls for the year 1860. The regressions for years $\geq$ 1920 include controls for waterpower plants added since 1900. Each presented coefficient based on individual regressions with 178 observations (Pre-periods N=177).

that adopted electricity later is mainly driven by the local decline in employment in other sectors rather than actual faster employment growth in services compared to districts that had adopted electricity early.

Figure A.7 presents the corresponding effect on change in total employment, Swiss population and foreign population. First, it highlights that there is no significant divergence in terms of employment or population in the pre-electricity period going as far back as 1850 with regards to the later adoption of electricity. Second, while there was no population growth between 1880-1900 the adoption of electricity appears to have increased both the Swiss (borderline insignificant) and foreign population in the period 1900-1920.

Third, the observed effect on population (measured at living location) stagnates after 1920 for Swiss and, especially, foreign population. In contrast, employment (measured explicitly at work location from 1955) continued to diverge. This divergence between population and employment likely reflects the increased potential for commuting post-WW2 (Swiss motorway construction started in the 1950s). These results seem to support that the early adoption of electricity had little impact on local population growth through migration or triggering a substantial demographic transition (population by age cohort is unfortunately not consistently available to study whether changes in death rates are offset by births). Further, they underline the persistent effect of the early adoption of electricity even though the interpretation of the estimated effect of early electricity adoption on local structural transformation after 1955 becomes more nuanced due to the apparent increase in commuting to those areas.

Figure 5: Effect of early electricity adoption on GDP per capita



Notes: The figure presents the IV-estimates for the effect of early electricity adoption per person on log GDP per person across cantons from 1875-2015 (with 5-year intervals). Estimates are based on an event-study, where the explanatory variable is interacted with time fixed effects so that the estimated coefficient can vary over time with 1885 being used as the reference year (the last year with no sizable electricity adoption). The presented effect size is for a one standard deviation higher exposure to electricity. Canton and time fixed effects are included as well. GDP per person 1890-2000 from HSSO (2012) and after 2000 from BFS (2019). GDP per person 1875-1885 estimated based on changes to per capita tax revenues across cantons from Department des Inneren (1891-1920). N=725 with 25 cantons and 29 time periods.

A natural question is whether these persistent differences in structural transformation were associated with long-run differences in GDP per capita, as we would expect. No historic information is available for GDP per capita at the district level, so that I use data at the more aggregate Canton level. Figure 5 presents the effect of early adoption of electricity 1880-1900 on GDP per capita across cantons 1875-2015. In line with the pattern of structural transformation observed at the district level, GDP per capita increased faster in cantons with higher electricity adoption 1880-1900. The estimates suggest that GDP per capita growth was on average 0.8% higher per year between 1885-1910 in cantons with a standard deviation higher exposure to electricity 1880-1900. Only the first and second World War reversed the divergence in GDP per capita for short periods of time. Only from 1970s income differences stabilized at a relatively constant level that persists up to today.

Evidence of the early electricity adoption having a long-run effect on incomes today also at the district level is provided in Table A.5. This estimate can plausibly be interpreted as causal as long as incomes pre-electricity adoption were not correlated with waterpower potential across districts. The previously presented evidence suggest that this should be the case. Column 1 presents the effect on median income in thousand Swiss francs across districts in 2010. Districts which had a one standard deviation higher exposure to electricity between 1880 and 1900 nowadays have a 2127 francs (4%) higher average income. A similar effect size can be observed for median incomes in column 2.

An important determinant of earnings between individuals is usually the level of education. In addition, secondary and tertiary education are crucial determinants of future economic growth (see e.g. Goldin & Katz 2001). Accordingly, observable differences in educational outcomes across districts would further support that there is a lasting effect of the early adoption of electricity on economic development. Indeed, districts earlier exposed to electricity also have a higher share of individuals with secondary (column 3) and tertiary education (column 4).[39] Accordingly, in a district with a one standard deviation higher exposure to electricity between 1880 and 1900 the share of the population with at least secondary education is estimated to be 2.02 percentage points higher and the share of tertiary education is 0.98 percentage points higher.

Two features are crucial to be able to conclude that the long-run effect is only from exposure in the initial 20 years of electricity adoption. First, the extension of the electricity grid across Switzerland rapidly equalized the use of electricity across districts after 1900. Access to electricity of firms in Switzerland rose from 5% in 1895 to 43% in 1911, and 94% in 1937 (see "Elektrifizierung" in HLS 2020). Universal access might however not be sufficient to conclude that the long-run effect was only due to initial differences as areas that adopted electricity early might have continued to use electricity more intensively even after the extension of the electricity grid (e.g. because of lower local electricity prices).[40] Table 6 analyses this formally, starting in Panel A by looking at the usage of electricity in factories in 1929. The effect of early adoption on electricity usage later on is

[39]Secondary education is classified as at least having received the Matura or vocational training, while tertiary education is having received a degree from a university or technical college.

[40]Comin & Mestieri (2018) show that not just differences in the timing of adoption of new technologies, but also the intensity of use, account for a large share of the observed differences in incomes across

shown in total kW (column 1), kW per firm (column 2) and kW per employee (column 3). In the first two cases a positive coefficient is observable, however per employee actually less electricity appears to be used, and all effects are statistically insignificant.[41] This is further confirmed by Panel B showing that there is no difference in electricity usage in all manufacturing and services firms also by 1955. These results suggest that the extension of the electricity grid in the early 20th century quickly led to a convergence in electricity usage between districts.

Table 6: Effect of early electricity adoption on long-run electricity use

	Electricity use in kW per		
	District	Firm	Employee
A. 1929	(1)	(2)	(3)
Δ Electricity pp 1880-1900	6017.18	141.92	-6.92
	(8775.68)	(526.02)	(15.90)
B. 1955			
Δ Electricity pp 1880-1900	20655.16	25.24	-0.45
	(30241.94)	(38.77)	(7.03)
Controls	Yes	Yes	Yes

Notes: The regressions present the IV results for the usage of electricity in total, per firm and employee in 1929 and 1955. For 1929 the outcome measure includes only factories, while for 1955 it covers all manufacturing and services. The 1929 data only reports total energy at the district level and measures were adjusted based on the usage of electricity versus other sources at the cantonal level (87.4% electricity of total energy). N=173(178) for 1929(1955). Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Second, one might be concerned that the persistent effect is mainly due to later increases in electricity generation which are correlated with the early adoption of electricity. For example, in France steam engines were more intensively adopted close to their first adoption in Fresnes-sur-Escaut (see Franck & Galor 2019). Importantly, due to controlling for the building of waterpower plants after 1900, the presented effect is purely from the early adoption of electricity, but not from future extensions in electricity generation. Indeed this post-1900 increase in electricity generation itself is positively related with industrialization itself (see Table A.6, longer-run results available on request). In line with the rapid extension of the electricity grid after 1900 across Switzerland, the effect of waterpower plants build for electricity generation is only associated with increased employment in electricity generation itself, but had no positive effect on other industries already in the period 1900-20. If not controlled for the magnitude of the impact of early electricity

countries. Indeed, the question of technology transfers has been a central theme in the convergence literature for a long time (see e.g. Bernard & Jones 1996).

[41] The numbers in column 1 and 2 are also small in economic terms considering that electricity generation increased by 1571% from 119350kW in 1900 to 1994067kW in 1930. So that the estimated effect from average early electricity adoption explains only about 1.5% of average electricity generation across districts in 1929 (corresponding to the higher manufacturing employment share, but not higher per capita electricity usage).

adoption on structural change is falsely overestimated by about 10%-20% across most results (presented in Figure A.6).

4.3 Decomposition of effect across industries

Table 7 analyses which industries are responsible for the observed persistent increase in employment in the manufacturing sector. Note, that the measured employment by industry here is based foremost on the respective individual's activity rather than the firm's.[42] This provides two insights: First it allows to distinguish whether the adoption of electricity affected mainly employment associated with the generation of electricity or those that used electricity. Second, it highlights which industries were the ones that gained from the adoption of electricity.

I focus on 7 consistently reported manufacturing industries "Electricity generation", "Construction, wood & stone products", "Machinery, watches, & other metal", "Chemicals", "Textiles & apparel", "Food products", and "Other". First, "Electricity generation" represents the direct rise in employment that is required for the generation and transmission of the electricity itself. The next two groups "Construction, wood & stone products" and "Machinery, watches, & other metal" are related on one hand to electricity generation through the need for building the electricity infrastructure and providing water-turbines. On the other hand, these industries might also have been affected through using electricity. The remaining four industry groups use electricity, but are not related to its generation in any straightforward way. Panel A presents the effect of electricity in the contemporaneous period 1880-1900, Panel B presents the effect for 1880-1920, and Panel C for 1880-1975.

Column 1 presents the effect of the adoption of electricity on the change in employment share in occupations in the "Electricity generation" industry. Unsurprisingly, the adoption of electricity increased employment in its generation and distribution by 1900. Notably, the effect persists over time, which suggests that the electricity generation infrastructure continues to be in operation even after 1900. Column 2 shows that there is also a positive employment effect on "Construction, wood & stone products" for 1880-1900. This accounts for most of the employment gains in manufacturing between 1880-1900, which suggests a important short-term employment effect of electricity adoption likely through the requirement to construct the new generation and distribution infrastructure.[43] However, this effect is only short-lived as after construction finished the positive employment effect disappeared and no effect is observable by 1920 or 1975. Column 3 suggests no

[42] This means that for example in a firm that produced chemical products and also generated its own electricity, a part of this firm's employment was recorded as chemical industry employment and another part as electricity generating industry employment. For example Bundesamt für Statistik 1900, Volume 3, p.1-5 provides a detailed description of the enumeration system used.

[43] The observed effect might of course to some extent also be due to the building and extension of factories in other industries that use electricity.

Table 7: Effect of electricity across manufacturing industries

	Generation	Mixed		Use of electricity only			
	Elec.	Con.	Mach.	Chem.	Text.	Food	Other
A. 1880-1900	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Δ Electricity pp 1880-1900	0.037**	0.378*	-0.006	0.102**	0.135	-0.078***	-0.036
	(0.017)	(0.205)	(0.074)	(0.041)	(0.156)	(0.029)	(0.041)
B. 1880-1920							
Δ Electricity pp 1880-1900	0.066***	-0.009	-0.077	0.114***	0.354*	-0.067	0.105+
	(0.011)	(0.077)	(0.119)	(0.043)	(0.211)	(0.062)	(0.071)
C. 1880-1975							
Δ Electricity pp 1880-1900	0.138***	-0.174	-0.790***	0.604**	1.194***	-0.093	-0.156+
	(0.035)	(0.203)	(0.223)	(0.278)	(0.398)	(0.099)	(0.108)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	178	178	178	178	178	178	178

Notes: The regressions present the IV results for the effect of electricity on the change in the share of employment across manufacturing industries 1880 to 1900, 1920 and 1975. Log waterpower potential per person is used as instrument for the change in electricity produced per person between 1880 and 1900. The change in electricity produced per person 1900-1920 and waterpower plants built 1900-1975 are included as additional controls, respectively. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

positive effect on "Machinery, watches, & other metal". This is not necessarily surprising considering that turbines were easily transportable to waterpower plants rather than manufactured locally (see "Turbinen" and "Maschinenindustrie" in HLS 2020). These three effects combined can be seen as the upper-bound of the direct effect of electricity generation on manufacturing employment. Together Column 1-3 explain a considerable share of the change in the manufacturing employment share in the short-run, but cannot explain the persistent effect observed by 1920 and 1975.

Column 4 presents the effect of early electricity adoption on employment in "Chemicals". This effect increases over time and explains 19%, 22%, and 83% of the higher manufacturing share by 1900, 1920, and 1975, respectively. This underlines the role of electricity in the establishment of the newly emerging chemical industry across Switzerland. The importance of electricity in new chemical production processes is presented in detail in Section 2.

The earlier ability to use electricity did not just contribute to the emergence of new industries, but also appears to have made existing ones more competitive. This is suggested by column 5 as employment in "Textiles & apparel" was positively affected from 1920 onwards. Notably, the "Textiles & apparel" industry had reached its peak employment and was already well established across Switzerland at the end of the 19th century. First, this highlights that at least locally electricity as a technology did not lead to the replacement of workers in the textile industry and rather increased employment. The use of electricity in the textile industry has been argued to have been especially beneficial for small scale producers and expanded the range of possibility for industrial production of textiles (Stiel 1933). Second, the positive effect here should be seen as slowing the decline of the textile industry and supporting the shift into new higher value products rather than necessarily creating new employment as overall the importance of the textile industry in Switzerland peaked in the late 19th century and declined after that (rising from 15% of total employment in 1860 to 19% in 1880, remaining stable at 18% till 1920 and collapsing to 4% in 1975). By 1975, the remaining employment in the Swiss textile industry was in innovative firms, which produced specialized products (e.g. for cars and planes, medical textiles, heat and other resistant textiles) and no longer low-value bulk goods (see "Textilindustrie" in HLS 2020).[44]

Column 6 suggests that in line with the decline in agricultural employment also employment in "Food products" (predominantly the making of cheese and meat products) declined by 1900. However, employment appears to have recovered afterwards to some extent. Column 7 reports little effect on the remaining industries (mainly typography, paper & mining).

The presented results suggest that the long-run effect of early electricity adoption on manufacturing employment was mainly from its use rather than its generation. By 1975, the increased employment in manufacturing observed is predominantly due to "Chemicals" and "Textiles & apparel", and only a fraction is explained by "Electricity generation". In all other industries lower employment is observed (with a significant decline for "Machinery, watches, & other metal"). This relative decline in other industries potentially reflects increasing industrial specialization in the second half of the 20th century as labor became more scarce.

Employment numbers vary considerably across those industry groups, so that while the presented coefficient provide direct insight on the contribution of the respective industry group to the overall increase in manufacturing employment, it does not reflect the importance of the early adoption of electricity within the respective industry group. The average adoption of electricity 1880-1900 explains by 1900 (1975): 27.1% (28.1%) of employment in "Electricity generation", 6.6% (-2.2%) in "Construction, wood & stone products", 46.8% (78.2%) in "Chemicals" and 1.5% (62.4%) "Textiles & apparel" across districts. This suggests that the majority of the spatial distribution of chemical industries (and the survival of textile industries) across Switzerland is explained by the early adoption of electricity, which again underlines the influence the early adoption of new technologies can have on economic activity even several decades later.

[44] The higher GDP per capita despite a persistently higher employment share in "Textiles & apparel", classically viewed as a less modern sector, suggests that a negative technological lock-in does not necessarily need to occur as documented in Franck & Galor (2019). Even those sectors can remain innovative in certain circumstances.

5 Mechanisms

5.1 Implausible mechanisms

There are a number of potential mechanisms which might explain the persistent effect of early electricity adoption on economic development. However, on the basis of previously presented results a number of them can already be ruled out. The first potential mechanism that seems implausible is that the divergence in economic development is driven by persistent differences in electricity generation across districts. While there is a persistent effect of early electricity adoption on employment in electricity generation, the effect is economically small compared to the persistent employment effect on industries that only gained from the use of electricity (see Table 7).

The second potential mechanism is that there was an incomplete technology transfer so that differences in the use of electricity and consequently economic development persisted over time (see e.g. Bernard & Jones 1996; Comin & Mestieri 2018). However, results in Table 6 show that, by 1929, early electricity adoption had no significant effect on electricity use. This suggests that the technology transfer was quickly completed across Switzerland ruling persistent difference in electricity use out as an obstacle to convergence.

The third potential mechanism often able to explain persistent differences in economic development even after initial advantages disappear is population or industry agglomeration due to sizable economies of scale (see e.g. Krugman 1991; Bleakley & Lin 2012).[45] However, again some of the already presented results appear to provide little support for this mechanism. First, there is no evidence of immediate population growth as there is no increase in migration into areas that adopted electricity early (Table 5). Nor does there appear to be evidence for sufficiently large enough population growth later on (Figure A.7). Instead local employment growth wa mainly driven by successive increases in male and female labor force participation and later likely commuting (Table A.4, Figure A.7). Further, even the observed employment growth starts to at least for some time slowdown again after 1900, rather than accelerate over-time as one would expect if this would be the mechanism (see e.g. Bleakley & Lin (2012)). Second, while the presented growth pattern of the newly developing chemical industries (Table 7) would be in line with increasing returns to scale and a cumulative process of local industry development due to a "historical accident" —the early adoption of electricity— as highlighted by Krugman (1991). The increased survival of employment in the textile & apparel industries, which peaked in importance by 1880, in locations that adopted electricity earlier cannot be explained by this. This as well as the fact that geographic constraints meant that early electricity adoption occurred to a large extent in remote areas of Switzerland, i.e.

[45]Note that in Krugman (1991) and Bleakley & Lin (2012) the initial location of economic activity is driven by factors increasing local demand for a particular product rather than the local supply of an input as in my case.

with a initial low population density and high transport costs, suggests that increasing returns to scale do not provide a satisfactory explanation for the persistent effect of the early adoption of electricity on economic development.

5.2 Human-capital accumulation

The evidence so far suggested that persistent differences in the use of electricity or population agglomeration are implausible mechanisms for explaining the persistent effect of the early electricity adoption on economic development. Instead, the evidence I collected suggests that human capital accumulation and consequent innovation are the most plausible explanation for the long run effect of the early adoption of electricity. Recent contributions in growth theory suggest that technical change can foster human capital formation (Galor & Moav 2006; Galor 2011),[46] which in turn is a main driver of economic growth (see e.g. Goldin & Katz 2001). Notably, Table A.5 already suggested higher levels of education today in districts that adopted electricity earlier. However, for this to be a plausible mechanism, there needs to be evidence of an immediate change in human-capital accumulation when electricity is adopted. I provide three pieces of evidence consistent with the hypothesis that the early adoption of electricity had effects on human capital formation and innovation. First, I show that educational outcomes immediately started to improve, especially in what can be considered the upper-tail in the 19th century. Second, I show that the education system as well as demand for it increased. Third, I show that this translates into a higher level of innovation today.

Table 8 studies how the early adoption of electricity influenced educational outcomes measured through military test scores. Conscription was nationally organized since 1874, covering the whole male Swiss population so that military test scores reflect the education level at age 19 across different districts. The test scores at the district level are based on the location of the primary school a recruit had visited. This is crucial as it was necessary at the time in Switzerland to migrate from sparsely populated districts to population centers to attend secondary schooling. Additionally, it helps to measure solely the effect on the local population and is not potentially biased by recent immigration. The top-mark received closely relates to educational attainments at the secondary level of schooling, while the worst two marks correspond to insufficient knowledge even at the primary level. Two exemplary maths questions highlight the level of knowledge evaluated. For the lowest mark one needed to fail simple questions evaluating the ability to add and subtract, e.g.: "An army division counts 538 officers and 10472 soldiers. How many men in total?", while to receive the top-mark one needed to answer complex multi-part questions: "Someone

[46]The mechanism in Galor & Moav (2006) is that the process of industrialization and the complementarity between capital and human capital lead to increasing support for the provision of public education that benefited both capitalists and workers.

obtained a loan of 2160 Francs with $4\frac{1}{2}\%$ interest. He paid back 2207.25 Francs for capital and interest. How many days did the loan last?"

Table 8: Effect of electricity on human capital accumulation

	Overall	Reading	Writing	Math	General
A. Secondary education 1880-1900	(1)	(2)	(3)	(4)	(5)
Δ Electricity pp 1880-1900	0.530*	0.476^{+}	0.667**	0.064	0.713**
	(0.306)	(0.351)	(0.338)	(0.358)	(0.310)
B. Secondary education 1880-1910					
Δ Electricity pp 1880-1900	0.932**	0.677*	0.784*	1.178*	1.089**
	(0.449)	(0.353)	(0.404)	(0.696)	(0.449)
C. Primary education 1880-1900					
Δ Electricity pp 1880-1900	0.088	-0.353**	0.154	0.037	0.310
	(0.316)	(0.178)	(0.460)	(0.327)	(0.612)
D. Primary education 1880-1910					
Δ Electricity pp 1880-1900	0.158	-0.259^{+}	0.246	0.517	0.129
	(0.232)	(0.168)	(0.341)	(0.479)	(0.314)
Controls	Yes	Yes	Yes	Yes	Yes
N	178	178	178	178	178

Notes: The regressions present the IV results for the effect of electricity from waterpower on the change in the share of top marks received (corresponding to a secondary level of education) and passing marks (corresponding to basic primary education) across different subjects 1880 to 1900/1910. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Panel A presents the effect on the share of top marks given to military recruits across four different subjects between 1880 and 1900. Column 1 shows the effect across all marks with there being a positive effect of electricity adoption on the share of top marks received. A standard deviation higher adoption of electricity increased the share of all top marks received by 2.7 percentage points. Column 2-5 provide the breakdown by the different subject areas tested. Column 2 presents the effect on reading scores, column 3 on writing, column 4 on maths and column 5 on general knowledge (Swiss geography, history and politics). Reading was the easiest subject with 32% receiving the highest possible mark in a subject, while general knowledge was the hardest subject with only 17% of tested recruits receiving the highest mark. Between 1880 and 1900 the overall effect is mainly driven by improvements in writing and general knowledge test scores. However, educational improvements will not immediately be fully observed as military recruits aged 19 were likely only affected by changes in the latter years of schooling.

Accordingly, Panel B looks at the period 1880-1910 reflecting the effect on educational outcomes a decade later (individuals tested were exposed to changes due to electricity adoption at least from age 9). Column 1 shows that the effect nearly doubles with a standard deviation higher adoption of electricity leading to a 4.7 percentage point increase in top test scores. By 1910, the largest improvement was in maths scores, while reading improved the least. In general, the result suggests the greatest improvement in educational outcomes occurred in the more complex subjects, which at the time represented upper-tail human capital.[47] Further, Panel C and D highlight that there is no comparable improvement at the primary level of knowledge, basic reading ability appears to have even declined briefly.[48] These considerable improvements in the share of well educated recruits across different subjects provides some evidence towards human capital being a plausible mechanism for explaining the persistent effect of the early adoption of electricity over time.

The second piece of evidence comes from the education system. In particular, the Swiss dual education system seems a plausible driver of the observed improvement in secondary education outcomes as it provided practical and theoretical knowledge specific to occupations and industries in part funded by employers. Table 9 looks at the effect of the early adoption of electricity on students in dual education in 1910 (Panel A) and newly established schools 1880-1910 (Panel B) based on the list of year-round operating schools reported in Grob (1887-1914). The effect is presented across all dual education, vocational schools at the secondary level of education, and polytechnic university departments at the tertiary level of schooling. Column 1-3 look at the effect across all districts for all dual education (Column 1), vocational schools (Column 2) and polytechnic universities (Column 3). A small, but insignificant, improvement in the dual education system is observable across these specification. However, the limited effect across all districts is not necessarily surprising as districts with a small population nearly never established dual-education institution of their own as they would in any case be underutilized. Instead in those areas it was common for students to temporarily migrate for the purpose of schooling.[49] For this reason, I focus on districts with above average population in Column 4-6. Here a clear positive effect of the early adoption of electricity on number of students and newly established dual education institutions is observable in Column 4. The estimated effect suggests that the average exposed district had 115 additional students and 0.6 newly established education institutions in 1910. A considerable increase considering the rarity of these upper-tail educational institutions. Column 5 suggests that the increase in students in 1910 was nearly completely from an increase in vocational schooling at the secondary level of education, and that this increase in student number is at least in part through the establishment of new vocational schools. In contrast, Column 6 suggests that there is little increase in students in polytechnic universities, however an increase in the num-

[47]The educational improvements associated with the adoption of electricity appear far broader than the limited (or even negative) effects found for the adoption of the steam engine in terms of working skills and literacy rates (see e.g. De Pleijt et al. 2018; Franck & Galor 2019).

[48]One explanation for this could be that some children in agricultural families, where child labor was still common at the time (see "Kinderarbeit" in HLS 2020), had less time for school as their labor needed to compensate for adult male workers that moved into manufacturing 1880-1900.

[49]The 1880 Census records nearly 1% of the population as pupils living outside their parents house.

ber of departments is observed, suggesting a reorganization rather than an extension of education.[50]

Further evidence on how the early adoption of electricity affected the education system is provided by Switzerland's direct democracy, which offers a unique opportunity to investigate individuals' support for the provision of government funded education. Table 10 Panel A presents the effect of early electricity adoption on support in referendums focused on increasing government spending on education and science. Column 1-6 show that areas earlier exposed to electricity persistently displayed higher support for government spending on education and research in the six referendums on this issues between 1902 and 1978 (unfortunately most referendums are observed after 1960 as education remained mostly a Cantonal and municipal issue). A standard deviation higher early adoption of electricity increased support for government funded education by as much as 9%. These national referendums of course did not necessarily lead to improved local education, but they suggest that individuals in districts that adopted electricity earlier valued education as early as 1902 more highly (borderline insignificant coefficient, but similar magnitude to later periods). This voting behavior should be strongly correlated with higher individual and municipal investments into education. Suggestive evidence (limited by data availability) for this is observable in increased municipal and cantonal spending, in particular for secondary education, across cantons (see Table A.7).

Table 9: Effect of electricity on dual education institutions

	All districts			Population centres		
	Dual	Voc.	Poly.	Dual	Voc.	Poly.
A. Students	(1)	(2)	(3)	(4)	(5)	(6)
Δ Electricity pp 1880-1900	0.717^{+}	0.375	0.343^{+}	5.737^{**}	5.345^{**}	0.392
	(0.531)	(0.356)	(0.222)	(2.450)	(2.458)	(1.654)
B. Schools						
Δ Electricity pp 1880-1900	2.183	0.395	1.787	28.576^{**}	10.891^{*}	17.684^{**}
	(2.342)	(1.070)	(1.475)	(11.271)	(6.502)	(7.593)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
N	178	178	178	63	63	63

Notes: The regressions present the results for the effect of electricity on the provision of dual education. In both secondary-level vocational schools and tertiary-level polytechnic university that operated throughout the whole year. Panel A presents the effect on number of students in thousands by 1910. Panel B on the establishment of new vocational schools and polytechnic university departments 1880-1910. Results are presented for all districts as well as for population centers only. Vocational schools comprise professional, craft, and commercial schools. The category of polytechnic universities by department also includes all design schools. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

[50]The latter effect appears to be driven in particular by the establishment of four new departments at the polytechnic university in Geneva, which however had considerably less students by 1910 than earlier established ones.

Table 10: Effect of electricity on education and infrastructure demand

A. Support education	1902 (1)	1963 (2)	1964 (3)	1973 (4)	1973 (5)	1978 (6)
Δ Electricity pp 1880-1900	0.940^{+}	0.168^{+}	0.483***	1.790***	1.256***	1.171***
	(0.667)	(0.117)	(0.131)	(0.674)	(0.304)	(0.274)
B. Support infrastructure	1877 (7)	1891 (8)	1897 (9)	1927 (10)	1945 (11)	1987 (12)
Δ Electricity pp 1880-1900	-0.696	-0.608	0.091	0.483*	1.178***	1.699***
	(0.605)	(0.547)	(0.703)	(0.265)	(0.361)	(0.411)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
N	178	178	178	178	178	178

Notes: The regressions present the results for the effect of early electricity adoption on the pro-votes in Swiss referendums on central government education and research spending in Panel A and infrastructure spending in Panel B. The referendums used are reported in detail in Table B.3. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 11: Effect of early electricity adoption on innovation today

	All patents (1)	Before 2000 (2)	After 2000 (3)	City (4)	Town (5)	Rural (6)
Δ Electricity pp 1880-1900	0.111***	0.053***	0.057***	0.003	0.042**	0.066**
	(0.033)	(0.016)	(0.021)	(0.009)	(0.020)	(0.029)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
N	178	178	178	178	178	178

Notes: The number of patents registered (1980-2017) per person (population in 2000) across Swiss districts using data from De Rassenfosse et al. (2019). Municipalities are classified based on population as city > 25000 inhabitants, town $10000 - 25000$ inhabitants and rural < 10000 inhabitants. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The third piece of evidence is that innovation persistently increased. This is one way through which human capital allowed manufacturing to persistently remain competitive and expand by consistently driving the development of new products. To evaluate this, I use data on geo-coded patents from De Rassenfosse et al. (2019) covering Swiss patents registered since 1980. Table 11 column 1 presents the effect of the early adoption of electricity on number of patents per inhabitant that have been registered over the last 40 years, which indeed suggests a higher level of innovativeness in areas that early adopted electricity. The estimate suggests that a district characterized by a one standard deviation greater early electricity adoption registered 28% more patents per person. Column 2 and 3 look at patents before and after 2000 suggesting that the rate of patenting remained stable and that there is no convergence across Switzerland in patenting. Column 4, 5 and 6 breaks the patenting down on whether the inventor was located in a city (>25000 inhabitants), town (10000-25000) or in a rural municipality with a population of less than 10000. The results suggest that early adoption of electricity mostly increased innovation in more rural areas. This would suggest that electricity at the end of the 19th century spread out innovation activities across Switzerland away from urban centers that are usually the main drivers of innovation to rather less densely populated areas.

5.3 Infrastructure network

The so far presented three pieces of evidence highlight the key role played by human capital formation and innovation in leading to persistent differences in economic development. However, the rather random nature of the early adoption of electricity across Switzerland, which was related to previously unimportant geographic characteristics rather than previous economic activity raises the question on how this high level of industrial specialization and innovativeness was feasible? In general, one would expect that high trade costs in these remote location should make high-levels of specialization in manufacturing and innovation unfeasible (Eaton & Kortum 2002).

One way in which this paradox can be resolved is that the infrastructure network adjusted to the early adoption of electricity reducing trade costs. I evaluate this in Table 12 by looking at the level of integration of districts into the Swiss railroad network today (accounting for about a third of transported goods and people). Column 1 looks at the number of operation points, location where loading and off loading occurs, measuring the density of the railroad network. The benefit of this is that it not just measures whether a railway line passes through an area, but also if there is actual activity along the line. The coefficient suggests that the number of operation points per square kilometer is 23% higher in areas that had a standard deviation higher exposure to electricity between 1880 and 1900. Next, column 2 looks at the number of tunnels build. This provides a good proxy of how much investment was undertaken to overcome major geographic obstacles to trade. Indeed more costly infrastructure investment was undertaken in districts adopting electricity earlier. Column 3 presents number of passengers per inhabitant today. Again a positive effect is observed in line with an adjustment in the infrastructure network as well as the previous highlighted increase in commuting.

This complementary role of infrastructure developments is further supported by Panel B of Table 10, which looks at the effect of early electricity adoption on support for government spending on infrastructure in referendums (1877-1987). The estimates suggest that there was no difference in demand before and during the period in which districts had an advantage in the adoption of electricity, but demand for infrastructure started to increase in the early 20th century and persisted after that. In 1987, a one standard deviation higher exposure to electricity increased support for “Rail 2000”, a major project of railroad improvements, by 8.5%. Accordingly, districts that adopted electricity earlier were able to become well integrated in the exchange of goods and knowledge. Here, of course Switzerland’s unique geographic position in the center of Europe might have been of crucial importance in impacting the gains from this. This observed improvement in infrastructure seems to be able to resolve the paradox that rather rural areas can have highly specialized firms and high rates of innovativeness. The presented increase in human capital and innovation in combination with this complementary change in connectivity provides a coherent explanation for how differences in economic development that emerged due to different electricity adoption for only 20 years continued to persist in the long-run despite electricity becoming adopted universally.

Table 12: Effect of early electricity adoption on the infrastructure today

	Operation points (per km^2) (1)	Tunnels (per km^2) (2)	Train journeys (per person) (3)
Δ Electricity pp 1880-1900	0.262^{*}	0.056^{*}	3.762^{***}
	(0.151)	(0.030)	(1.253)
Controls	Yes	Yes	Yes
N	178	178	178

Notes: Swiss railway operation points on line as of 2020, tunnels as of 2019, passenger numbers as recorded at train stations in 2018. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

6 Conclusion

This paper documents that the early adoption of electricity in the late 19th century persistently increased industrialization and incomes across Switzerland with areas being differentially exposed for a brief period of only about 20 years. The persistently higher level of industrialization is related to the establishment of the chemical and pharmaceutical industry across Switzerland, which required electricity for many novel production processes, where the early adoption of electricity can explain a majority of the distribution of employment observed by 1975. In addition, in areas that adopted electricity early the textile industry, the pre-eminent industry by 1900, was more likely to outlast increasing competition during the 20th century.

Human capital accumulation and a complementary adjustment in the infrastructure network appear to be important mechanisms for the persistent divergence in economic development due to the early adoption of electricity. So that, areas earlier adopting electricity remained more innovative up to today. In contrast, electricity itself does not appear to be an important mechanism. Differences in the use of electricity quickly disappeared as the electricity grid expanded and persistent differences in electricity generation are small in terms of economic importance. Further, at least initially no in-migration occurred suggesting that the change in the economic structure occurs internally.

To obtain these results I exploit exogenous variation in the potential to produce electricity from waterpower across Switzerland to deal with the issue that technology adoption is usually highly endogenous. The initial geographic constraints on the adoption of electricity led to its early adoption not just in urban centers, where new technologies are usually first adopted, but equally in rural and remote areas. This is important as it highlights that early exposure to new technologies can foster economic development also in relatively poor and rural areas at the time. It also underlines that certain geographical features can have a lasting effect on economic development despite being economically relevant for only an extremely short period of time.

These results help explain how some countries were able to develop and retain their economic lead, when exposed to new technologies early. It also highlights that long run gains of new technologies might be quite heterogeneous with electricity having been far more beneficial compared to the steam-engine (see Franck & Galor 2019). Further, it highlights that countries might gain considerably from attracting skill-biased technologies and industrial sectors through positive externalities on human capital accumulation. It however also cautions that new general-purpose technologies like information and computer technologies might have long lasting positive or negative effects far beyond disruptions caused in the labor market during their implementation.

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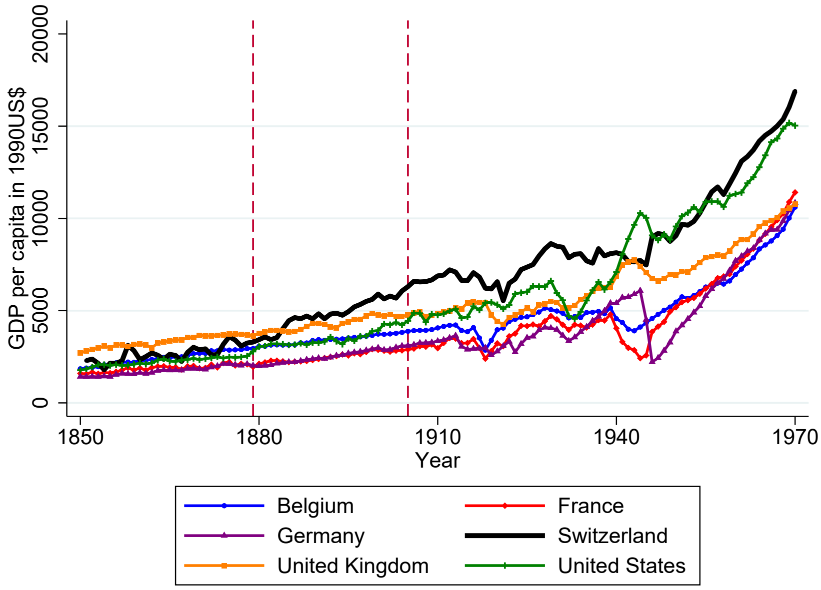
Online Appendix

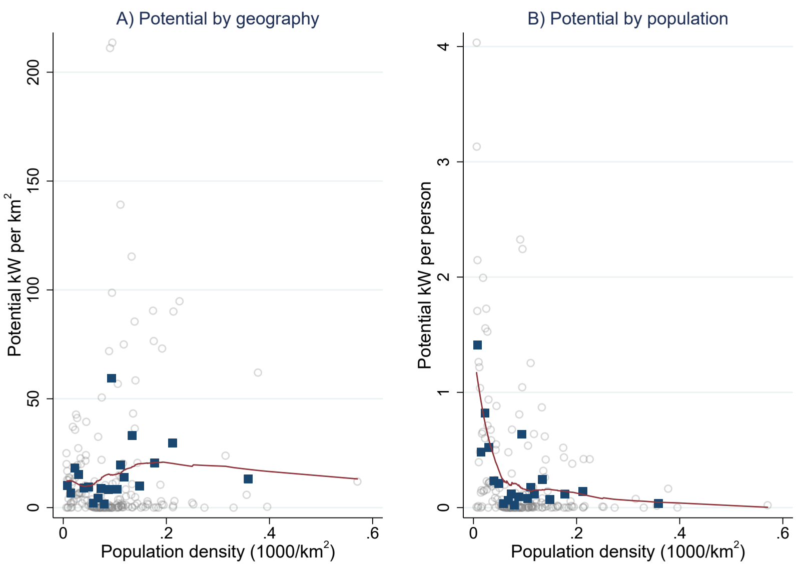
A Figures & Tables

Figure A.1: Economic output across countries 1850-1970



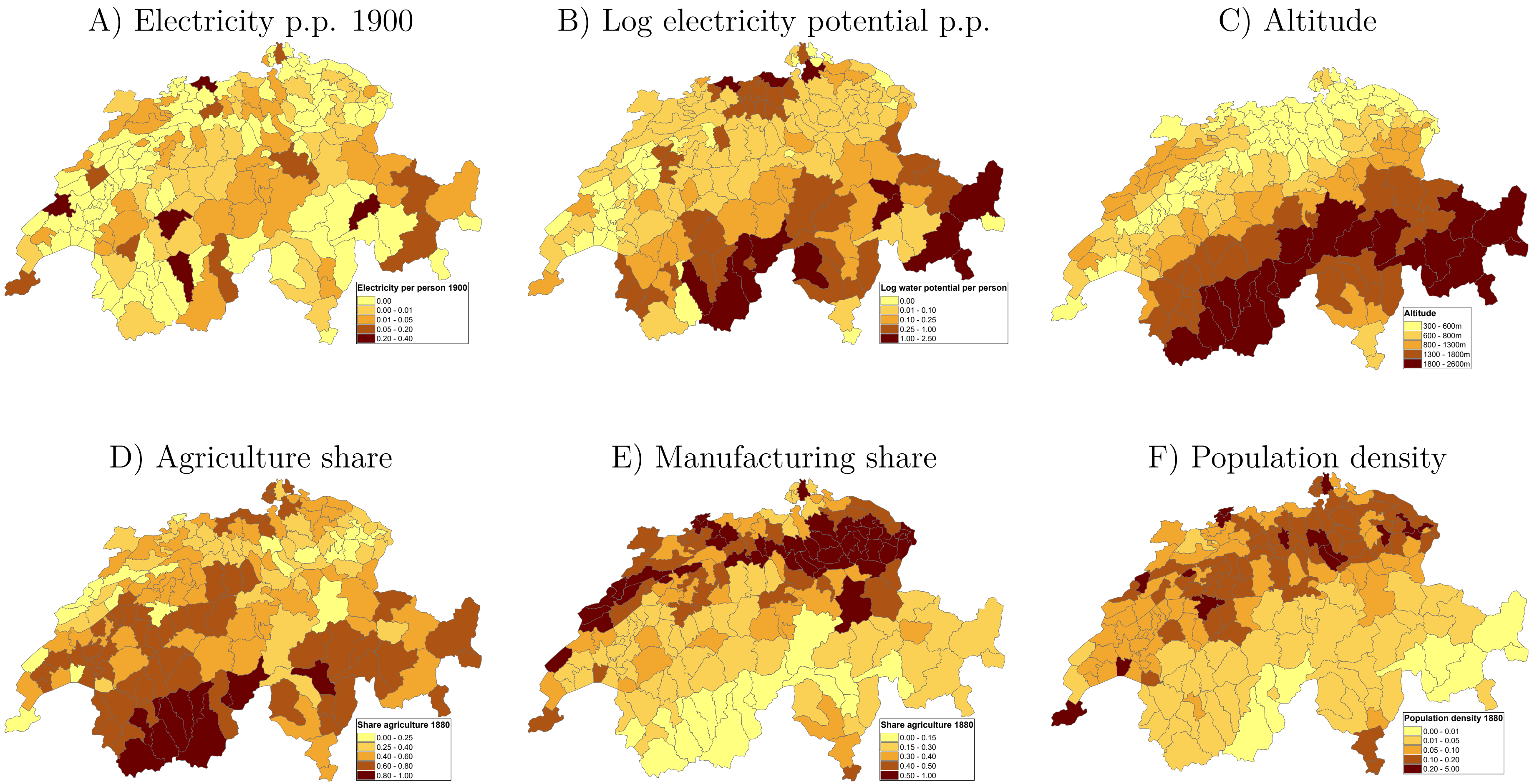
Notes: Real GDP per capita in 1990US$ across main industrial countries and Switzerland from 1850-1970. The first line in 1879 reflects the initial commercial usage of electricity in Switzerland. The second line is 1905 when Switzerland had the highest per capita electrification in the world with this leadership quickly diminishing in the following years (see "Elektrifizierung" in HLS 2020). Source: Bolt et al. (2018)

Figure A.2: Random allocation across areas versus population



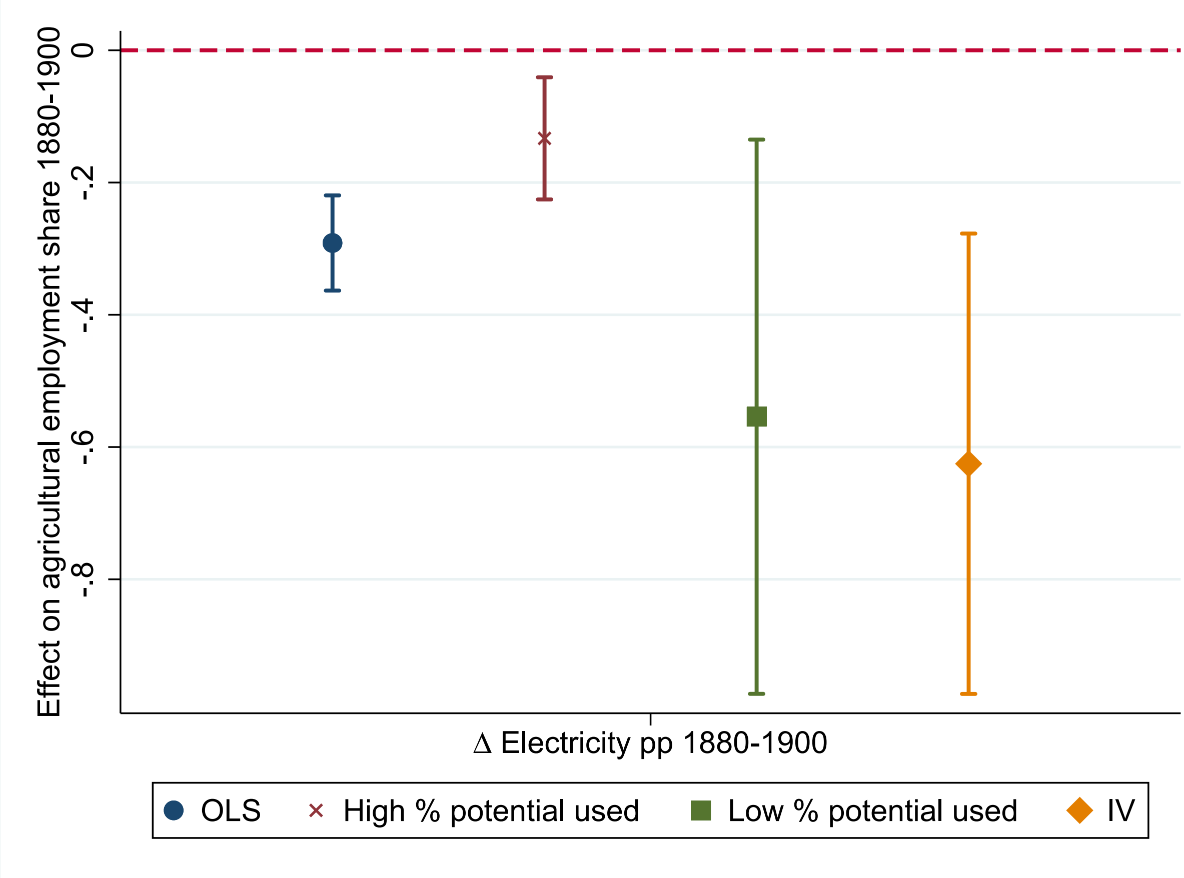
Notes: The figures depict the relationship between waterpower potential in kW per (i) km^2 and (ii) person with population density in 1880. Even when waterpower potential is as good as randomly distributed across Switzerland in terms of geography more densely populated grid cells mechanically have a lower per capita potential for electricity generation. Blue squares represent binned observations. Hollow grey dots correspond to the underlying observations. The solid red line is the lowess fit.

Figure A.3: Descriptive maps for Switzerland



Notes: The figures depict A) kW of electricity per person in 1900, B) log water power potential, C) altitude, D) agricultural employment share in 1880, E) manufacturing employment share in 1880, and F) population density in 1880. More detail available when zooming into the respective figure.

Figure A.4: Evidence on source of bias in the OLS



Notes: This figure presents baseline OLS and IV estimates and highlights that the downward bias in magnitude in the OLS is due to areas that utilize a large share of their potential for electricity generation ($> 20\%$) as they have a smaller marginal effect from adoption compared to those areas that are only able to utilize a small share ($< 20\%$). N=178; 66; 112; 178

Table A.1: Additional robustness checks for the effect of electricity adoption on agricultural employment share

	Additional human characteristics					**Additional geographic controls**					**All**
A. OLS	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Δ Electricity pp 1880-1900	-0.305***	-0.298***	-0.305***	-0.288***	-0.280***	-0.294***	-0.284***	-0.291***	-0.290***	-0.273***	-0.269***
	(0.042)	(0.047)	(0.046)	(0.044)	(0.033)	(0.038)	(0.040)	(0.044)	(0.044)	(0.049)	(0.052)
Share top math scores	-0.104^{+}										-0.067
	(0.065)										(0.083)
Share Catholic		0.008									0.016
		(0.022)									(0.030)
Share Jewish		-0.914									-0.360
		(0.792)									(0.781)
Share Romansh			-0.070^{+}								0.013
			(0.046)								(0.029)
Share Italian			-0.012								0.054
			(0.040)								(0.053)
Share French			-0.017								-0.009
			(0.022)								(0.049)
Liberal constitution (1833)				0.016							0.092^{+}
				(0.016)							(0.056)
Sonderbund member (1845)				0.031^{+}							0.199***
				(0.019)							(0.049)
Cantonal FE					Yes ✓						Yes ✓
Cropland						0.085***					0.035
						(0.020)					(0.030)
River							-0.017**				-0.006
							(0.006)				(0.008)
Average water flow								-0.001***			-0.001***
								(0.000)			(0.000)
Alpine									-0.007		-0.004
									(0.016)		(0.022)
Po Basin									0.055***		0.073***
									(0.004)		(0.012)
Ruggedness										-0.093*	-0.096
										(0.047)	(0.086)
B. IV											
Δ Electricity pp 1880-1900	-0.661***	-0.575***	-0.595***	-0.585***	-0.497*	-0.600***	-0.512***	-0.546***	-0.635***	-0.601***	-0.406*
	(0.240)	(0.211)	(0.178)	(0.224)	(0.281)	(0.211)	(0.193)	(0.194)	(0.210)	(0.221)	(0.210)
F-stat (1st stage)	14.86	12.14	15.11	16.35	13.61	16.51	17.53	15.37	16.77	16.45	7.97

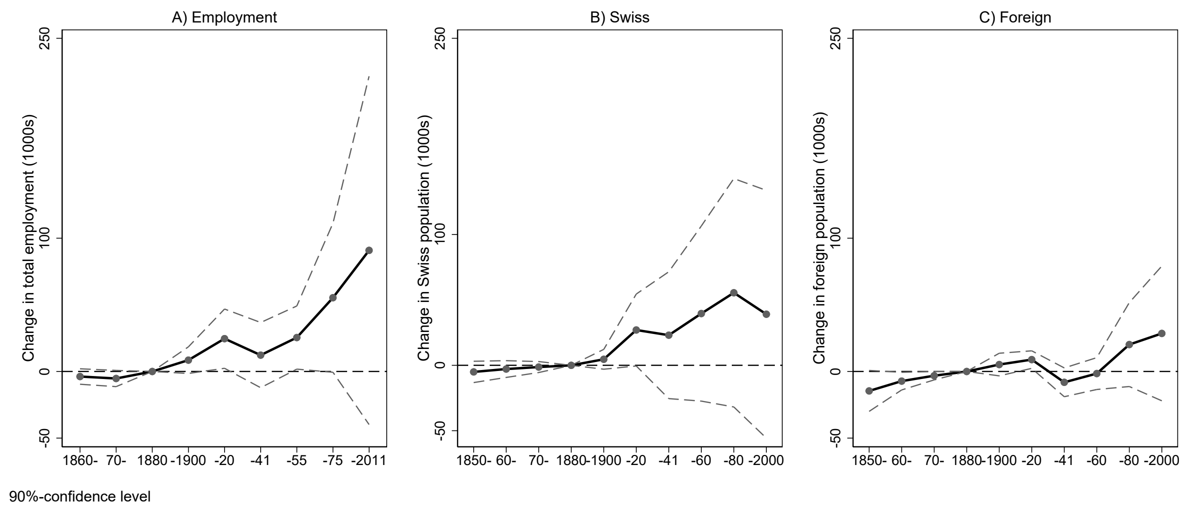
Notes: This table extends on column 5 of Table 4. The dependent variable is the change in the share of employment in agriculture between 1880 and 1900. N=178. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.2: Pre-trend analysis

	Agriculture		Manufacturing		Services	
A. 1860-1880	(1)	(2)	(3)	(4)	(5)	(6)
Δ Electricity pp 1880-1900	0.087	0.388	-0.348	-0.210	0.260	-0.177
	(0.552)	(0.400)	(0.436)	(0.260)	(0.320)	(0.193)
B. 1860-1870						
Δ Electricity pp 1880-1900	0.298	0.340^{+}	-0.458	-0.061	0.227	-0.257^{+}
	(0.400)	(0.232)	(0.369)	(0.165)	(0.203)	(0.194)
C. 1870-1880						
Δ Electricity pp 1880-1900	-0.215	0.048	0.111	-0.149	0.035	0.079
	(0.293)	(0.223)	(0.126)	(0.201)	(0.225)	(0.202)
F-stat (1st stage)	36.17	17.46	36.17	17.46	36.17	17.46
Controls	No	Yes	No	Yes	No	Yes

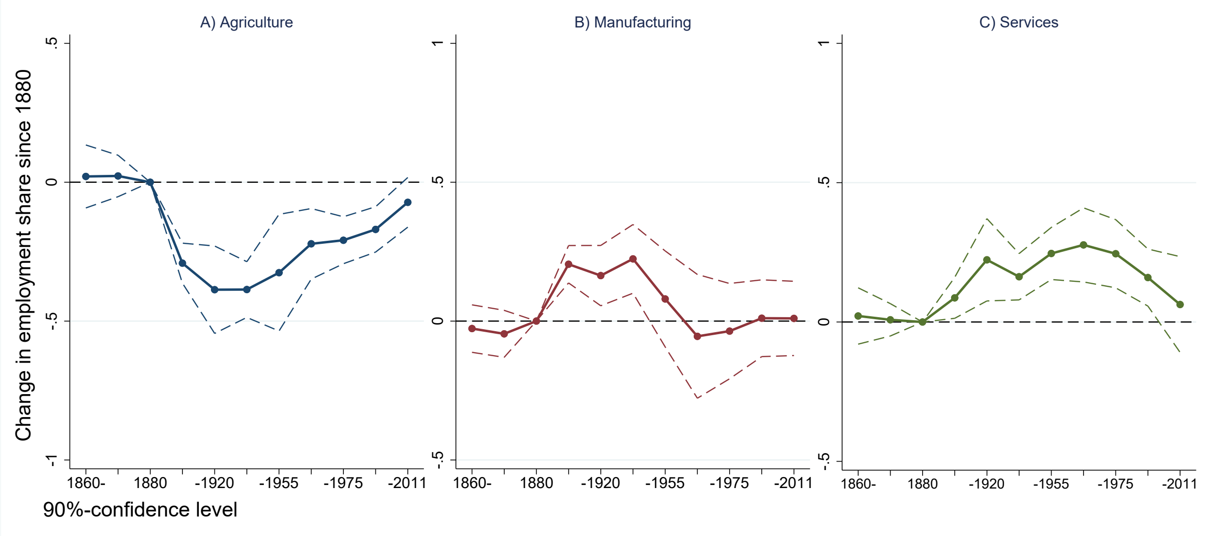
Notes: The table analyses whether there is any correlation between the instrumented electricity adoption per person between 1880-1900 and outcomes 1860-1880 before the commercial adoption of electricity. The dependent variable is the change in the share of employment in agriculture, manufacturing and services between 1860 and 1880 for different sub-periods. One less observation is available as two districts were created out of one in 1877. Initial controls are for 1860. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Figure A.7: Effect of early electricity adoption on employment and population



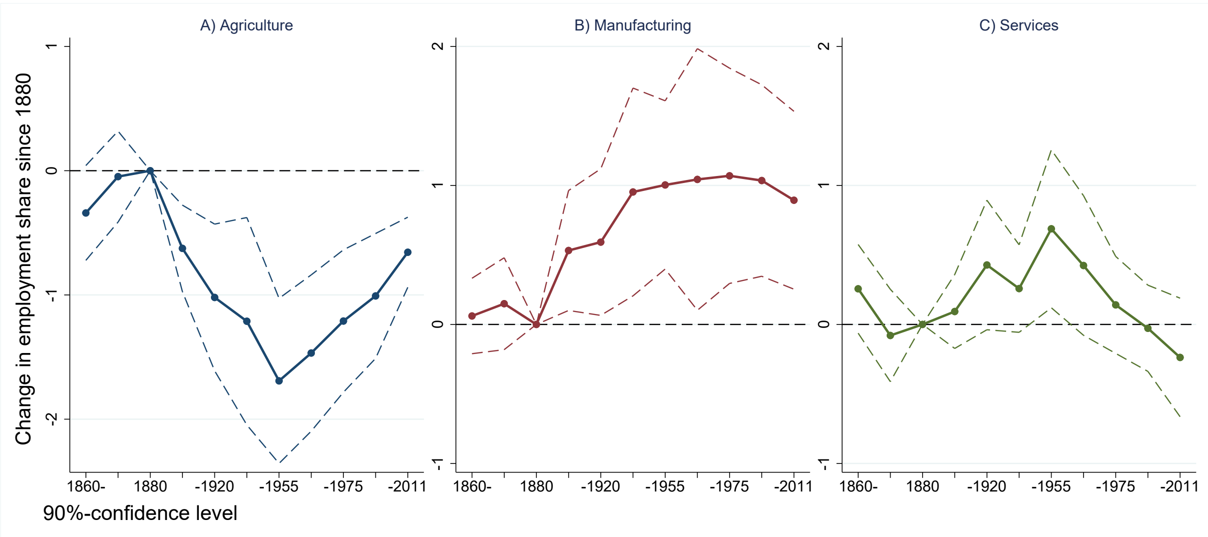
Notes: The figure presents the IV-estimates for the effect of early electricity adoption per person 1880-1900 on the change in total employment, Swiss population and foreign population from 1880 to the specified year. Dependent variable change in number rather than growth rate due to the small number of foreigners in 1880 providing a bad denominator for the growth rate over the long-run. Results using employment growth similar (smaller standard errors). The instrument used is log waterpower potential per person. Regressions include the full set of baseline controls and robust standard errors are clustered at the cantonal level. The regressions for years $\geq$ 1920 include controls for waterpower plants added since 1900. Each presented coefficient based on individual regressions with 178 observations (Pre-periods N=176).

Figure A.5: OLS estimates for the effect of electricity adoption



Notes: The figure presents the corresponding OLS estimates to Figure 4.

Figure A.6: Effect of electricity adoption confounded by later adoptions



Notes: The figure presents the corresponding IV estimates to Figure 4 without controlling for the adoption of electricity after 1900.

Table A.3: Effect of electricity adoption on employment growth by sector

	Employment growth rate		
	1880-1920	1920-1975	1975-2011
A. Agriculture	(1)	(2)	(3)
Δ Electricity pp 1880-1900	-0.922**	-0.333*	0.147
	(0.421)	(0.183)	(0.281)
B. Manufacturing			
Δ Electricity pp 1880-1900	6.103**	7.819**	0.881
	(2.608)	(3.815)	(0.866)
C. Services			
Δ Electricity pp 1880-1900	7.661**	2.452	-0.515
	(3.142)	(1.999)	(1.805)
Controls	Yes	Yes	Yes
N	178	178	178

Notes: The table presents IV estimates for early electricity adoption on employment growth rates in agriculture, manufacturing and services for different periods. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.4: Effect of electricity adoption on employment growth by gender

	Employment growth rate		
	1880-1900	1900-1920	1920-1941
A. Overall	(1)	(2)	(3)
Δ Electricity pp 1880-1900	1.242***	0.986*	-0.040
	(0.456)	(0.542)	(0.313)
B. Male			
Δ Electricity pp 1880-1900	1.549***	-0.369	-0.298
	(0.464)	(0.576)	(0.322)
C. Female			
Δ Electricity pp 1880-1900	0.021	2.105**	0.653
	(0.202)	(0.966)	(0.728)
Controls	Yes	Yes	Yes
N	178	178	178

Notes: The table presents IV estimates for early electricity adoption on growth rate of employment for the periods 1880-1900, 1900-1920 and 1920-1941. Panel A, B and C present total, male and female employment growth. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.5: Effect of early electricity adoption on current outcomes

	Income		*Education*	
	Average (1)	*Median* (2)	*Secondary* (3)	*Tertiary* (4)
Δ Electricity pp 1880-1900	42.543*	26.922*	0.405***	0.196***
	(25.777)	(14.460)	(0.146)	(0.036)
Controls	Yes	Yes	Yes	Yes
N	178	178	178	178

Notes: The table presents the IV estimates for electricity adoption 1880-1900 on level of modern development. Column 1 and 2 presents the effect on average and median income in thousand Swiss francs across districts in 2010. Column 3 and 4 presents the effect on the share of individuals with secondary and tertiary education in 2000. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.6: Electricity adoption and industry employment 1900-1920

	Elec. (1)	Con. (2)	Metal (3)	Chem. (4)	Text. (5)	Food (6)	Others (7)
Δ Electricity pp 1900-1920	0.006***	-0.001	-0.001	0.001	0.002	-0.001	-0.002+
	(0.000)	(0.004)	(0.004)	(0.002)	(0.004)	(0.001)	(0.001)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	178	178	178	178	178	178	178

Notes: The table presents the estimates (OLS) for change in electricity generation 1900-1920 on the change in the share of employment across manufacturing industries 1900-1920. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A.7: Effect of electricity on education spending

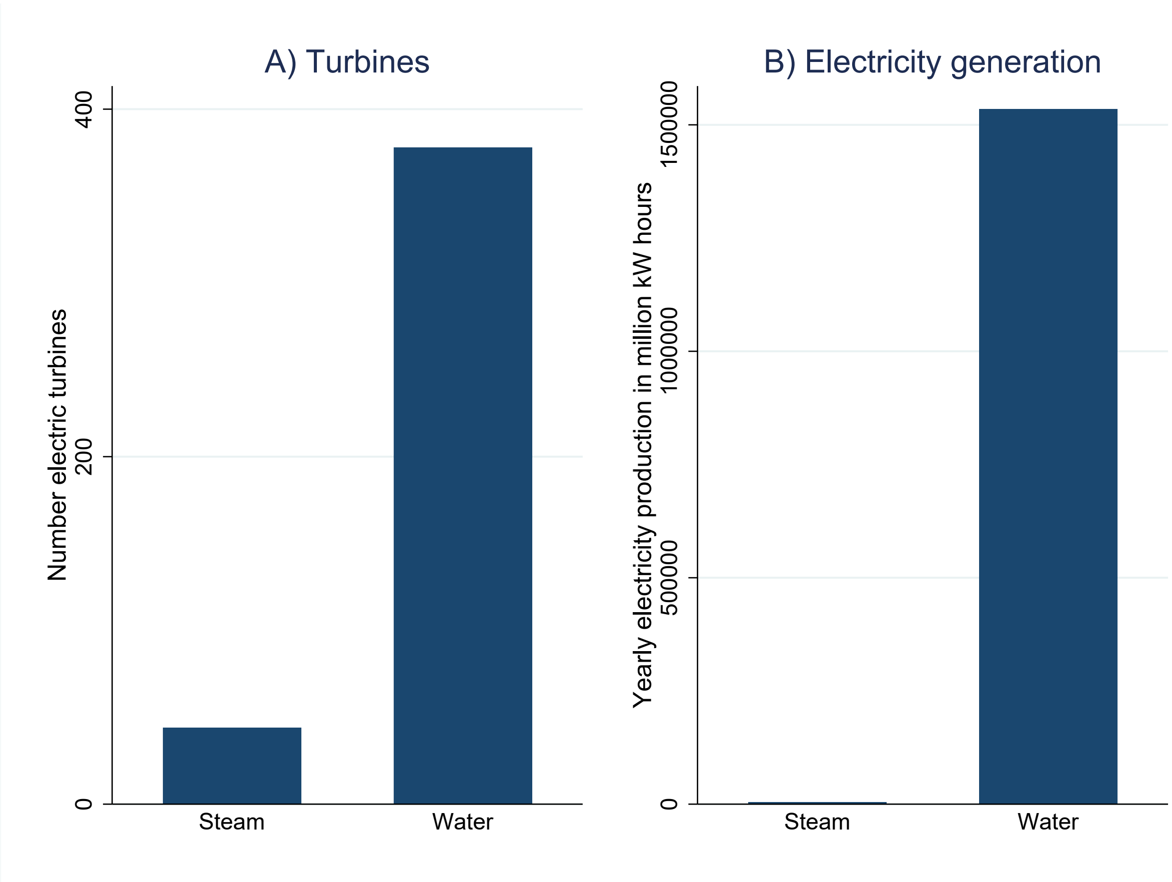
	Primary (1)	Secondary (2)
Δ Electricity pp 1880-1900	0.730*	9.846**
	(0.406)	(4.951)
Controls	Yes	Yes
N	25	24

Notes: The table presents IV estimates for electricity adoption on the change in municipal and cantonal education spending (1887-1900) at the primary and secondary level. Data was only available at the cantonal level from 1887 onwards. Robust standard errors in parentheses. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

B Data Appendix

B.1 Electricity data

Figure B.1: Electricity production in Switzerland by power-source



Notes: Type of turbines by number and actual kW hours of electricity produced over a year in 1916. To the best of my knowledge 1916 is the earliest year power from steam turbines is recorded. Reported steam turbines include those located within waterpower plants (actually the majority of steam turbines installed). Source: Department des Inneren 1891-1920.

My data on electricity production by waterpower plants and waterpower potential is collected from "The waterpower of Switzerland in 1914" (Bossard 1916) compiled by the water-management agency ("Abteilung für Wasserwirtschaft") of the Swiss department of the interior ("Department des Innern").[51] The electricity produced from waterpower represented the vast majority of electricity production in the early stages of electrification in Switzerland (see Figure B.1). The low importance of steam power for electricity production was due to Switzerland being scarce in natural resources and requiring expensive

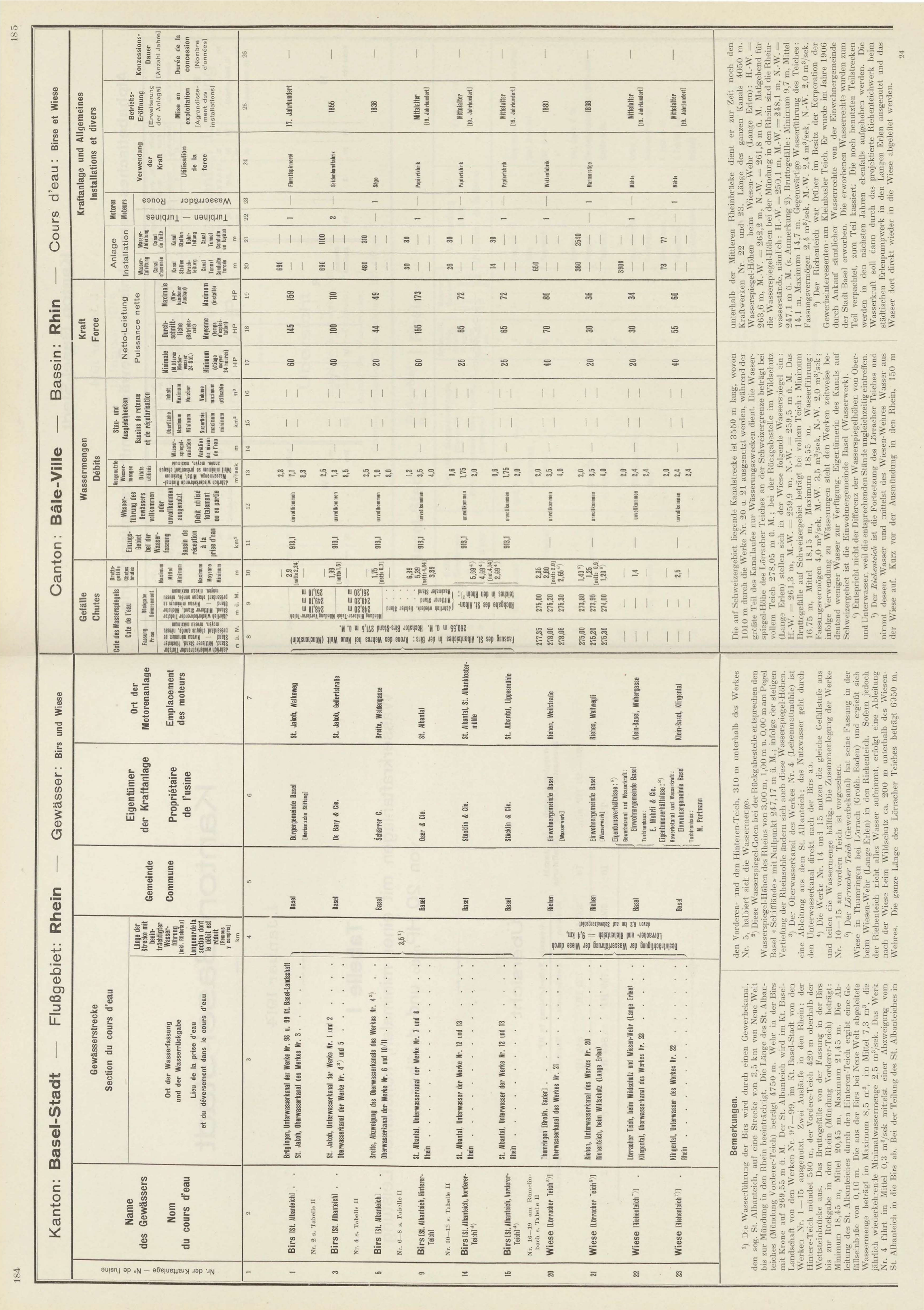
[51]The historical information used was jointly created by a group of engineers working for the Swiss water-management agency, cantonal power-plants, the Swiss Federal Railway and Fa. Locher & Cie (a private construction company). The objective of the assigned project was to map all existing and potential waterpower plants in detail across Switzerland to obtain information of current generation and ownership of waterpower plants as well as plan the building of future waterpower plants across Switzerland with the aim to maximise national electricity generation.

coal imports. This made the generation of electricity from coal uneconomical (Bossard 1916). Even the remaining negligible generation of electricity from coal appears to have been mostly located at waterpower plants to compensate for variations in the water level (Roth 1920). This is the main reason the actual energy generated by steam turbines is even more negligible.

Further, the distribution of electricity due to technological constraints was only possible over short distances until the beginning of the 20th century with many waterpower plants operating at low-voltages, supplying specific (usually industrial) establishments. Even the 49 high-voltage power plants that existed in 1901 on average supplied electricity over a maximum distance of 9.4km with the longest distance being 35km (2nd: 28km; 3rd 21km, see Department des Inneren 1891-1920). High-voltages (usually above 1000volt) are a prerequisite for providing electricity over long-distances to avoid excessive transmission loses. Even this select sample of high-voltage power plants by 1901 on average only supplied electricity to only 5 municipalities (the average district had 18 municipalities). Even the "Société des forces électriques de la Goule" in Saint-Imier covering the longest distance of 35km supplied a mere 29 municipalities and 29000 people. In contrast, by 1908 the number of high-voltage power plants had increased to 280 with the longest transmission distance extended to 135km(See Department des Inneren 1891-1920). This shift in the way electricity was supplied is corresponding to a drastic shift in the generation of electricity from small private suppliers to Cantonal companies at the start of the 1900s as described in HLS (2020) "Elektrizitätswirtschaft". For waterpower plants that lay within multiple district boundaries, the respective allocation of energy generated is reported for each administrative unit separately in Bossard (1916). Accordingly, my measure captures well district-level electricity adoption 1880-1900 as a whole due to generation and supply of electricity having been extremely localized.

The first part of the newly digitized data —used for the main explanatory variable— from "The waterpower of Switzerland in 1914" provides information on the water source (e.g. river, lake, etc), location (municipality and district), ownership, specific features of the plant, the minimum, average and maximum power generated, the installed turbines, the different types of utilization of the power, construction (and extension if applicable) date and a vast set of other information of all mechanical and electrical waterpower plants with a capacity of at least 15kW (corresponding to 20HP, the unit in which energy was recorded in Bossard 1916). An example page of the data source is presented in Figure B.2. I use the average power generated as the measure of energy supplied by a power-plant and allocate this energy to two groups: (i) electric power plant if the power utilization specifies that the harnessed energy is converted into electricity, e.g. stating that the purpose of the energy was the transmission of electrical power or the supply of electrical light and (ii) mechanical power which is all other uses that are not indicating that the energy generated was converted into electricity. I use the location information to match the respective power

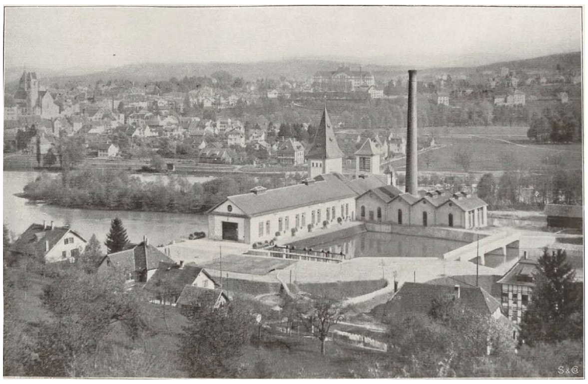
Figure B.2: Example page for waterpower plants reported



Notes: The figure shows an example page (in German and French) from Bossard (1916) reporting existing waterpower plants. It reports information on name, water-body, location, ownership, slope, water statistics (including origin, usage degree, flow, dam size), power generated, pressure pipes for in and outflow, turbines and waterwheels, opening and extension dates, and concession duration (if known).

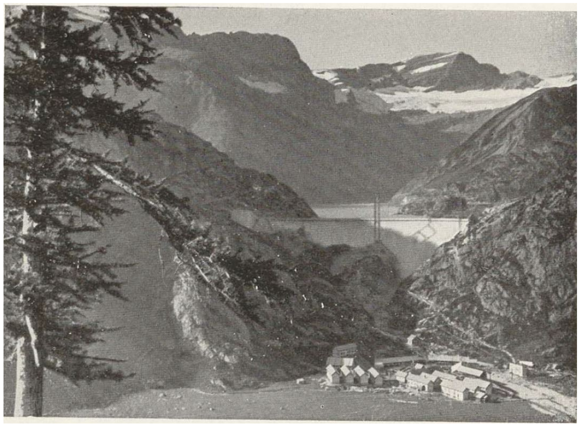
Figure B.3: Examples of waterpower plants

A) Without embankment dam



Waterpower plant build in Aarau in 1894 owned by the municipality of Aarau with a 705kW electricity production. Figure 2 depicts a waterpower plant without embankment dam using a pressure pipe.

B) With embankment dam



Waterpower plant build in Barberine in 1923 owned by the Swiss Federal Railways with an electricity production of up to 15000kW and an embankment dam capacity of 39000000m^3.

plants to Swiss districts. The location information in the table is provided for districts ("Bezirke") and municipalities ("Gemeinden") with a corresponding map providing precise geographic information as well that can be matched to the respective waterpower plants. Following this, I use the date on construction and extensions to construct measures of the electric and mechanical waterpower generated for specific time periods (allocating an equal weight to each extension date).

The second part of the data —used for the instrument— is based on digitized information presented in the main map in "The waterpower of Switzerland in 1914". This map gives the precise location of existing and potential waterpower plants and their specific features through illustrations of the existing and planned canals, pressure pipes towards and out of the turbine house, and whether an embankment dam is required. I geocode each existing and potential waterpower plant based on the proposed location of the turbine house. The mapping of whether a waterpower plant existed is based on 1914, however this does not affect my variable of the potential as I combine both existing and potential waterpower plants into a single measure for the potential, while I use the information from the first set of data for my explanatory variable. In correspondence with this, in cases were the map marks that both a waterpower plant already exists, but it could be extended to generate more energy, I use the maximum potential of the respective location, but do not count the already existing generation. This means my measure of potential electricity generation reflects the maximum potential electricity generation independent of whether any of this potential is already exploited or not.

Potential waterpower plants can be distinguished into two specific groups those not requiring an embankment and those requiring an embankment. Illustrations of the two

Table B.1: Geographic correlates with waterpower potential

	Waterpower potential		*Potential (with dam)*	
	(1)	(2)	(3)	(4)
Altitude (km)	708.338	367.690	8188.837***	6672.395***
	(1188.243)	(899.725)	(2267.789)	(1799.255)
Ruggedness	4327.011	1937.109	692.845	-2.8e+03
	(3739.482)	(3561.099)	(5128.420)	(5193.128)
Longitude	431.633	100.981	1239.455+	410.900
	(614.706)	(545.445)	(875.785)	(776.011)
Latitude	876.845	608.684	47.966	350.428
	(2535.380)	(2159.705)	(2978.637)	(2637.971)
Average river speed		255.235***		263.704***
		(47.107)		(60.939)
Number river segments		0.005**		0.012**
		(0.002)		(0.005)
adj. R^2	0.031	0.264	0.320	0.474
N	178	178	178	178

Notes: The table shows the correlation between geographic characteristics and the waterpower potential in kW across districts. Potential waterpower plants without embankment dam in columns 1 & 2. Potential waterpower plants with embankment dam in columns 3 & 4. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

types of waterpower plants are provided in Figure B.3. Waterpower plants requiring embankment dams were only build from 1908 onwards and only two existed by 1914. Accordingly, potential waterpower plants requiring an embankment dams are not actually relevant for the building of waterpower plants by 1900. Including these would provide a less relevant first stage.[52] Waterpower plants without and with an embankment dam are distinctly identifiable on the historical map. For this reason, I code waterpower plants requiring an embankment dam separately and do not count their waterpower potential towards a district's potential used in the instrument.

Columns 1 & 2 of Table B.1 show the geographic features across districts that are correlated with my measure of waterpower potential. Major geographic differences in altitude, ruggedness, longitude and latitude across districts appear to have little association with waterpower potential. The main correlate of waterpower potential appears to be the number of river segments and the average water flow speed of these segments. Note that these segments in Switzerland are predominantly minor mountainous creeks and rarely shippable rivers (or of any other economic relevance before electricity). Of course, average flow speed should be driven by ruggedness at the detailed local level, however this needs to be interacted with the flow pattern of local creeks to be of importance. This

[52]In addition, one might be more concerned that the decision on where to locate an artificial lake for the embankment dam might be influenced by considerations other than maximizing electricity output (avoiding the destruction of economically viable land). However, the map does illustrate several embankment dams that would have required the flooding of multiple villages and smaller towns.

Table B.2: Embankment dams and early electricity adoption

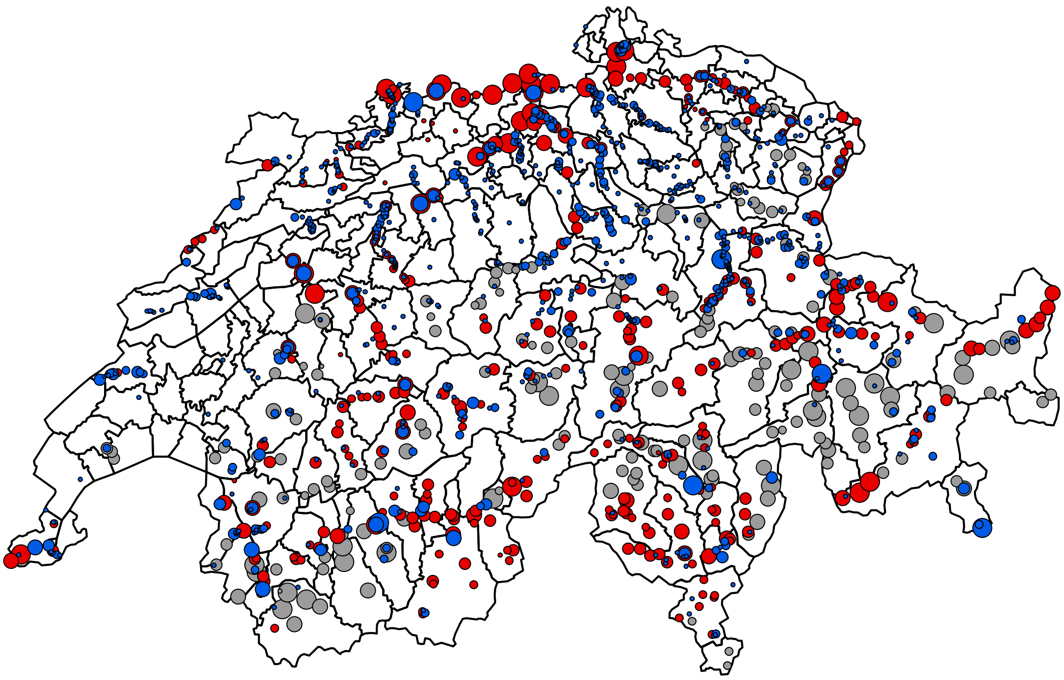
A. 1880-1900	(1)	(2)	(3)	(4)
Log waterpower potential pp	0.057^{***}			
	(0.014)			
Waterpower potential pp		0.038^{***}		
		(0.010)		
Log embankment waterpower potential pp			0.020	
			(0.017)	
Embankment waterpower potential pp				0.004
				(0.006)
B. 1900-2011				
Log waterpower potential pp	2.403^{***}			
	(0.359)			
Waterpower potential pp		1.425^{***}		
		(0.188)		
Log embankment waterpower potential pp			2.361^{***}	
			(0.360)	
Embankment waterpower potential pp				0.589^{***}
				(0.205)
Controls	Yes	Yes	Yes	Yes
N	178	178	178	178

Notes: Panel A Column 1 and 2 present the relationship between (log) waterpower potential per person (excluding all embankment dams) and actual adoption of electricity per person 1880-1900. Column 1 is the first-stage of the baseline specification in Table 4 Column 5. Column 3 and 4 estimate the same relationship for potential embankment dams and electricity adoption. Panel B presents the relationship between the respective waterpower potential and the building of waterpower plants from 1900 to 2011. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

again underlines that my measure of waterpower potential is associated with minor local geographic features rather than more major geographic differences of districts across Switzerland. Notably, the $R^2 = 0.264$ suggests that there is also considerable variation still left to be explained, e.g. reflecting features surrounding the available waterflow like the suitability for the construction of pressure pipes that can only be adequately accessed by a systematic analysis of the local geography by engineers. It is also worth pointing out that columns 3 & 4 suggest that major geographical features (altitude) play an important role for the building of potential waterpower plants with embankment dams. This is not surprising considering that for most embankment dams in Switzerland large mountains are a necessity (see also Figure B.3).

Table B.2 provides evidence that potential waterpower plants with embankment dams were indeed irrelevant by 1900. Panel A shows that potential power plants without embankment dams are highly relevant for the adoption of electricity, while potential waterpower plants with embankment dams do not provide a relevant first-stage for the adoption of electricity by 1900. Panel B shows that potential waterpower plants with embankment dams becomes a relevant instrument after 1900 for the location of waterpower plants. It also underlines the changing nature of waterpower plant construction over time, but that the measure of log waterpower potential used as instrument still remained to some extent relevant for later waterpower plant construction.

Figure B.4: Location of existing and potential waterpower plants 1914



Notes: The map shows the existing and potential waterpower plants in Switzerland in 1914 digitized based on the originals in Figure B.5. Blue dots represent existing and red dots represent potential waterpower plants. Both using available natural water sources. Grey dots represent existing and potential waterpower plants that require the building of an embankment dam. These are coded separately and not used for the instrument as the first of these was only build in 1908 and only two existed by 1914. The sites are coded into 5 categories represented by dot size: (i) 20-99HP, (ii) 100-999HP, (iii) 1000-4999HP, (iv) 5000-9999HP and (v) above 10000HP with 1HP being equal to 0.75kW. Source: Bossard 1916

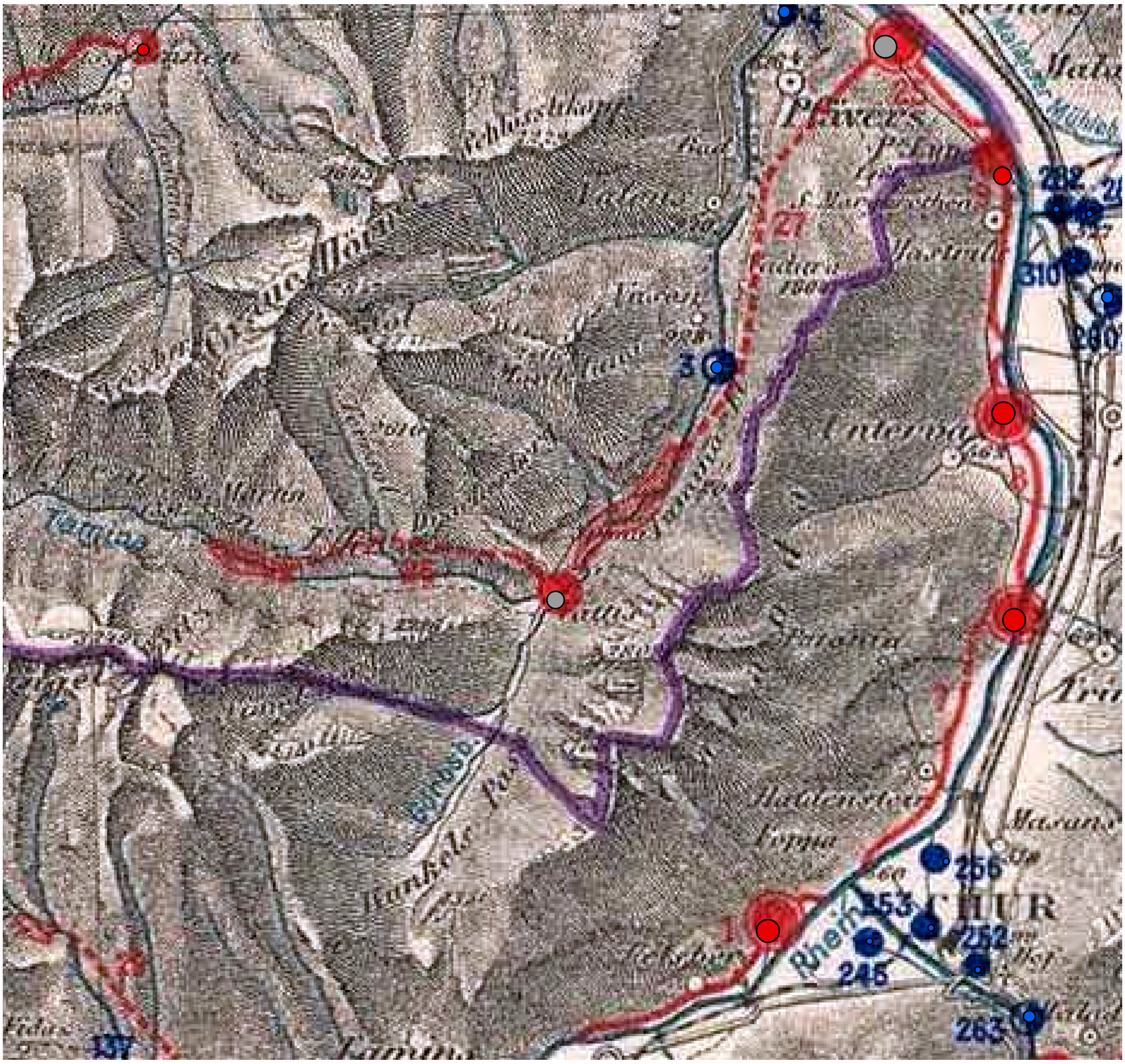
Figure B.4 presents the map of all existing waterpower plants in 1914 and potential power plants across Switzerland digitized based on the originals presented in Figure B.5. An excerpt of the corresponding original map with the individual coding is illustrated in Figure B.6. The map provides the waterpower for existing and potential waterpower plants in 5 distinct categories: (i) 20-99HP, (ii) 100-999HP, (iii) 1000-4999HP, (iv) 5000-9999HP and (v) above 10000HP with 1HP equal to 0.75kW. For each category its respective lowest value is used to construct the waterpower potential. Also, the map measures power for existing and potential waterpower plants based on constant minimal kW (i.e. the lowest water level throughout the year). To construct the district level waterpower potential the capacity of all blue and red dots are summed up (apart from where a red circle represents that the existing waterpower plant could be expanded). These existing

Figure B.5: Original maps for existing and potential waterpower plants

Notes: Original maps depicting existing and potential waterpower plants. Source: Bossard 1916.

and potential waterpower plants marked with blue and red dots in Figure B.4 correspond to the potential waterpower plants depicted in Figure 1 in the main text.

Figure B.6: Extract from historic map of potential waterpower



Notes: The figure shows an extract of the map from Bossard (1916) of existing (blue) and potential (red) waterpower plants in Switzerland in 1914. Straight and doted lines represent the connection between sites through pressure and tailback lines, when these lines originate at a point of the map it represents the source of the water used. I code, represented by the overlying circles, the sites accordingly apart from cases where an embankment dam is required. The embankment dam is denoted in the map by a red (blue) shaded area for potential (existing) dams. These sites requiring a dam are coded as a gray dot instead of their original color. Numbers associated with dots link them to detailed information presented in table format. Purple lines represent administrative boundaries.

B.2 Employment data

To assess the effect of electricity on economic development, I need data on employment by sectors (agriculture, manufacturing, services) across Swiss districts. This allows to measure structural transformation a key part of the process of economic development (see e.g. Kuznets 1973). I collect this data from the Swiss Census focussing on employment across agriculture, manufacturing and services for the years 1860, 1870 1880, 1900, 1920, 1941, 1955, 1965, 1975, 1985 and 2011 (see Bundesamt für Statistik 1860-2011).[53] These provide information on employment of individuals for the whole of the Swiss population at the district level. Further, I collect information on manufacturing sectors for the years 1880, 1900, 1920 and 1975 for 7 consistent industry groups:[54] "Electricity generation", "Construction, wood & stone products"[55], "Chemicals", "Textiles & apparel", "Food products", "Metal, machinery & watches", and "Other". The category "Other" is mainly comprising employment in mining, paper and typography, but some newly emerging industries (e.g. rubber products) not associated with any of the other categories gain some importance after 1880.

One issue faced when combining district level data for this long period is that geographical boundaries change. In general, administrative boundaries in Switzerland remained relatively stable over time. However, a few districts were merged or divided at some point in the sample period. I aggregate these into the larger unit for the whole sample period.[56] Figure B.7 depicts employment shares in agriculture, manufacturing and services over time. The figure highlights that up to the 1960s a transition from agricultural to manufacturing employment and services. The figure also highlights considerable disruptions during WW2 and the subsequent decades despite Swiss neutrality. After the 1960s, the service sector share of employment increased while the share of agriculture and manufacturing employment started to decline. However, while the share of agriculture fell below

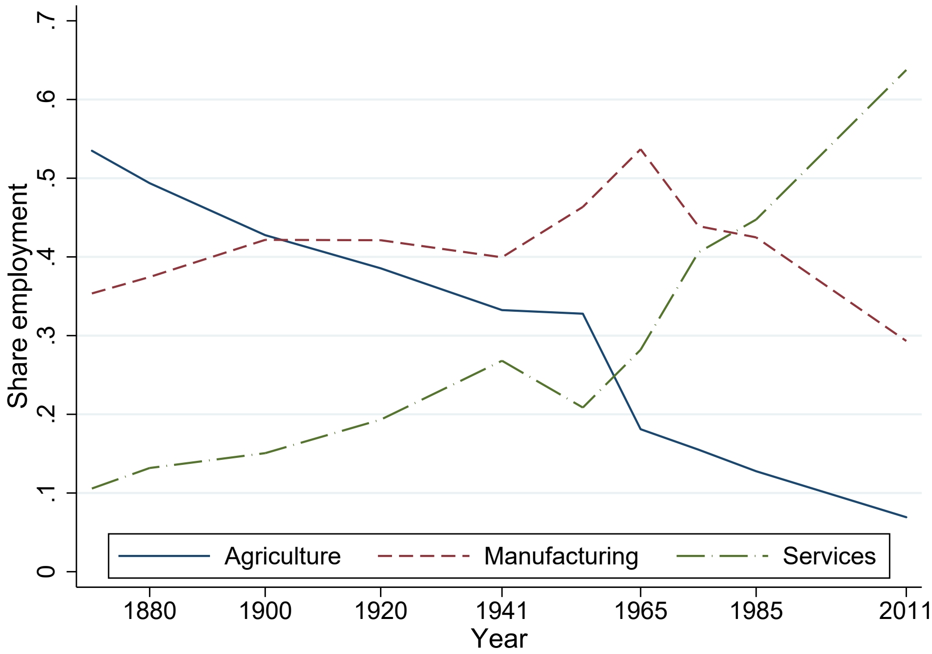
[53]Location of employment till 1941 is based on residence, and after 1955 on workplace (using the firm census instead of the population census). Initially, data is only available by residence from the population census, however differences between residence and workplace should be minor before the 1950s.

[54]While aiming to create as consistent industry groups as possible over time, in a few cases certain types of smaller occupations were reassigned from one industry category to another without there being detailed enough information at the district level to resolve this issue. For example in 1880, industry category "F4. Papier- und Holzstofffabrikation", i.e. the making of paperstock (not paper), reported at the cantonal level is only reported within a more aggregate broader chemical industry category ("F. Chemische Gewerbe") at the district level and matched to "Chemicals". In 1900, paperstock is no longer reported individually, but within "118. Herstellung von Papierstoff und Papier", the making of paperstock and paper, with paper being part of the more broad typography category ("D. Typographische und bezügliche Gewerbe"), which was matched to "Others". Employment in both had to be matched to "Others" in 1900 despite employment in paper stock having been part of "Chemicals" in 1880.

[55]Construction is included within manufacturing because even in the disaggregated historical information for 1880-1920 the construction of buildings is reported in one category together with the production of materials predominantly used for construction (wood and stone products). Accordingly, I follow the historic classification and count construction within manufacturing.

[56]This is the case for Bucheggberg-Kriegstetten, Dorneck-Thierstein, Geneva, Olten-Gösgen, Solothurn-Lebern and St.Gallen-Tablat. Some minor boundary changes that occur between districts that I do not account for between 1860 and 1975 due to their negligible nature are the following ones: Territory changes from Nidau to Biel district in 1920, Arbon to Bischofszell in 1924, Arbon to Bischofszell in 1935, Moudon to Echallen in 1960. From 1976 onwards the frequency of district boundary changes accelerates or districts get abolished as an administrative level in some Cantons altogether. I circumvent this issue by matching more detailed municipality-level or geocoded information to my historic district boundaries.

Figure B.7: Structural change in Switzerland 1860-2011



Notes: The figure depicts the share of employment in (i) agriculture, (ii) mining and manufacturing and (iii) services. The share reported is the average across the 178 districts in the sample. Sources: Bundesamt für Statistik 1860-2011

10 percentage points, manufacturing employment remains important accounting for 30 percentage points of employment in the average district.

B.3 Other data sources

To analyze the channels through which the effect of early electricity adoption persists I collect data on electricity usage for 1929 and 1955 from the census (Bundesamt für Statistik 1860-2011) to analyze whether areas adopting electricity early still use more electricity at later points in time. Data on the education level of the population is collected from 1880-1910 military test scores reported in Statistischen Bureau (1880-1910) to see whether districts adopting electricity early experience higher levels of human capital accumulation. This is augmented with data on education spending at the cantonal level and information on number and students of dual education institutions from Grob (1887-1914), and on patenting by De Rassenfosse et al. (2019). Infrastructure data is obtained from SBB (2020). Swissvotes (2019) provides district level information on voting outcomes in Swiss national referendums since 1870 allowing to measure changes in political demands. A list of the referendums used by category is presented in Table B.3. HSSO (2012) and BFS (2019) are used for GDP data at the cantonal level from 1890 to 2015 and combined with information on tax revenue across cantons from Department des Inneren (1891-1920) to obtain proxies for GDP for the preceding years 1875, 1880 and 1885. Swiss and foreign population data across districts comes from the Swiss census (Bundesamt für Statistik 1860-2011) using the already digitized municipality-level population counts in "Daten der Gemeinden 1850-2000" and aggregating the data to my district boundaries.

This is complemented by a set of datasources used in the construction of control variable. Longitude and latitude data is based on a digitized map of Swiss districts obtained from the 1900 census (see Bundesamt für Statistik 1860-2011). The average altitude of a district is calculated using topographical information (1km x 1km grid) from the elevation map of Europe (European Environment Agency 2004). The area of districts obtained in the same way is combined with population data from the census to construct 1880 population densities. Religion and primary language spoken across districts also comes from the 1880 census. The share of cropland is constructed based on Ramankutty et al. (2010). Information on main and tributary rivers is obtained from Kelso & Patterson (2009). Data on different ecoregions is from Olson et al. (2001). The intial education level is based on the military test scores (Statistischen Bureau 1880-1910). The remaining initial controls (agricultural employment share, population density, religion, language) used are obtained from the 1880 census (Bundesamt für Statistik 1860-2011).

Table B.3: List of Swiss federal referendums

	No	Date	Referendum	Direction	Yes	Turnout
	Investment education & science					
1	59	23.11.1902	Subsidies primary schools	Pro	76.3%	46.6%
2	205	08.12.1963	University & vocational training stipends	Pro	78.5%	41.8%
3	207	24.05.1964	Reform job related education	Pro	68.6%	37.0%
4	234	04.03.1973	Reform education system	Pro	52.8%	27.5%
5	235	04.03.1973	Support scientific research	Pro	64.5%	27.5%
6	286	28.05.1978	University subsidies	Pro	43.3%	48.9%
	Government infrastructure subsidies					
7	20	19.01.1879	Subsidies for the alpine railways	Pro	70.7%	61.9%
8	39	06.12.1891	Purchase of the Centralbahn	Pro	31.1%	64.3%
9	53	20.02.1898	Government purchase & operation railways	Pro	67.9%	78.1%
10	103	15.05.1927	Subsidies for alpine roads	Pro	62.6%	55.3%
11	138	21.01.1945	Debt relief of the SBB state railway	Pro	56.7%	52.9%
12	348	06.12.1987	Rail 2000	Pro	57.0%	47.7%

Notes: Referendums voted on in Switzerland on government education and innovation policy, and infrastructure investment. The reported list presents the first six referendums that focus on these clearly defined issue and are comparable over time. For government education and innovation policy referendums I focus on expenditures, but exclude referendums focused on the redistribution of power across different levels of administration. For government infrastructure investment I focus on subsidies and expenditures of the central government that are not linked to any specific taxes financing these infrastructure projects. Data from Swissvotes (2019), which is also used for the classification of referendums.

C Historical Appendix (not for publication)

C.1 The electrification of Switzerland

Switzerland was at the technological forefront in the adoption of electricity. The first recorded commercial use occurred in 1879 at the Hotel Engadiner Kulm in St. Moritz, where electrical lamps were supplied by a small waterpowered generator.[57] At the turn of the century Switzerland was leading in per capita electricity production (81.9kWh in 1902, and 166.9kWh in 1907, see "Elektrifizierung" in HLS 2020),[58] just in front of the United States (81.7 kWh in 1902; 125.2 kWh in 1907).[59]

A key feature of Swiss electrification was its heavy reliance on waterpower due to the absence of coal deposits. This meant that use of this new source of energy was initially unequally distributed across Switzerland and dependent on the proximity to sites where the forces of nature could be used to produce electricity due to the absence of long-distance transmission. More than 1000 sites across Switzerland were deemed to be able to generate more than 15kW electricity. However, the potential electricity generation differed vastly across these sites with 126 of these being used to generate electricity by 1900). The gradient of a river segment combined with complementary features like river bends or confluences were crucial in determining the amount of electricity that could be generated at a site (see Bossard 1916, Volume 4, p.15-16). Indeed this meant that most locations are along small, rocky streams with little economic or geographic significance prior to 1880 rather than major rivers like the Rhine, Rhone and Aare. This reliance on waterpower is also recorded in the Swiss statistical yearbook, which estimates that more than 99%

[57]Electrical lighting, motors and dynamos were invented by the 1840s, however it took until the 1880s for electricity to become economically used as a source of power and light. The first electric tram started operating in Berlin in 1881. The first commercial power plant, Edison's Pearl Street Station, was opened 1882 in New York serving initially 400 lamps of 82 customers. In the same year, the city of Lausanne introduced electrical street lights. In 1886 the Thorenberg plant was opened in Switzerland, the first that used alternating current to provide electricity to consumers (Weingartner 2016).

[58]Converting the electric power of hydroelectric-plants recorded in my data, the electricity production per person is 144kWh in 1900, however this measure based on Bossard (1916) reflects maximum electricity that could be generated from the installed turbines conditional on available seasonal water-level variations, but does not account for power-generation being reduced due to lower demand or turbines being completely shut-off over night potentially explaining the observed discrepancies in measures. Taking into account that electricity (especially for manufacturing) is sparsely needed for 8 hours overnight and on Sundays suggests a very similar 82kWh electricity generation per person.

[59]Directly comparing installed capacity using primary sources provides a similar picture. Based on the data collected from Bossard (1916) the total installed capacity of Swiss electrical power-plants was 69,000kW (548kW on average) in 1900. The US census of electrical industries (US Department of Commerce 1912) records 1,390 water and 5,930 steam turbines with a capacity of 328,854kW and 1,034,955kW in 1902, respectively. This suggests that installed electricity generation capacity per capita in Switzerland was about 20% greater than in the US. The reliance on however likely implied that this capacity was less intensively utilized than in the US as installed turbine capacity in Switzerland was about 1.7 times higher than the maximum electricity that turbines actually could generate due to fluctuations in the water-level throughout the year (see Bossard 1916). This historical electricity generation is tiny compared to the 698 Swiss plants operating in 2018 having an average capacity of 25572kW (Eidgenössische Amt für Wasserwirtschaft 1928-2018).

of electricity produced was from waterpower plants by 1920 (see Data Appendix B.1 for more detail).

Interestingly, waterpower was not just crucial for electricity generation in Switzerland, but the development of electric power generation and transmission was in return crucial in allowing the exploitation of the available waterpower potential. This was due to mechanical energy generation and transmission by watermills having only been able to harness a fraction of the energy that waterpower was able to potentially provide. The main constraint was that waterwheels and transmission by shafts and belts was simply unable to handle and distribute large amounts of energy that turbines and electric transmission lines were able to exploit. [60] Even tough watermills were only able to exploit a very limited amount of power they still were of considerable historic importance in the early stages of industrialization until the advent of the steam engine (Mokyr 1992).

The emergence of electricity as a power source required investment in power plants and transmission lines. In the early stages of electrification, up to the 1890s, about 50% of electricity production was from power-plants build by firms for their own consumption (see Figure ??).[61] However, improvements in transmission technology lead to electricity use rapidly becoming more widely available. This was in particular due to the emergence of a specialized electric utility industry which focussed exclusively on generation and distribution of electricity to consumers.[62] By 1895, only 5% of firms across Switzerland had access to externally generated electrical power (see “Elektrifizierung” in HLS 2020). However, the share off firms connected to the electricity grid quickly rose to 43% in 1911 and 95% in 1937. Further, the improvements in electricity transmission also meant that plants initially built to supply specific industrial plants increasingly supplied excess electrical energy to others (see Bossard 1916). This underlines that electricity being supplied through central power generation meant that fixed investment were not necessarily required by individual firms to use electricity.[63] In a similar way, in cases where power-plants had

[60] A detailed historical description of the changes in generation and transmission technology from mechanical waterpower over steam to electrical power is provided in Volumes I-III of Hunter & Bryant (1979-1991).

[61] Some important examples are the chlorate factory in Saut-du-Day of the Pariser Société d’électrochimie, the calcium carbide, ethin and fertilizer production of Lonza, and the Alusuisse establishing the first aluminium plant in Europe as well as producing other electro-chemical products since 1888 (“Elektrizitätswirtschaft” in HLS 2020).

[62] The low cost of electricity usage is highlighted by balance sheet calculations of US engineer C. E. Emery in 1896 which suggest the total cost of generating one unit of energy from steam-power on site was about 4-5 times as expensive (especially due to the fixed capital investment required on-site) as the price charged for electrical energy supplied from a power-station off-site (see Emery 1896). This was particularly beneficial to small-scale firms which could draw energy as needed from the electricity network, in contrast to most technological developments during the industrial revolution which were scale-augmenting (Mokyr 2010).

[63] The investment required to use it varied greatly by application, for example small electric heaters versus large electric arc furnaces. That energy could be used as needed is generally seen as one of the advantages of electricity over steam-power, and why it was particularly beneficial to small-scale producers (Mokyr 2010).

been initially built by firms for their own consumption, generation and use of electricity usually developed into distinct businesses as the electricity grid expanded.

The development of the Swiss electricity grid occurred in three distinct phases (see "Elektrizitätswirtschaft" in HLS 2020). In the early phase (1880-1900) electrification was dominated by private firms and focussed on local supply. In the second phase (1900-WWI) public producers and distributors became more important with electricity starting to be supplied over longer distances. In the last phase (after WWI) interconnected networks for delivering electricity across the whole of Switzerland were established. This transition was helped by improvements in technology leading to vast increases in transmission distances at the start of the 20th century. In 1901, the longest transmission line in Switzerland was 35km doubling to 72km in 1904 and 135km by 1908 (see Department des Inneren 1891-1920). Accordingly, the maximum number of municipalities supplied from a single power-plant increased ten-fold from 29 in 1901 to 232 in 1908. Consequently, local suitability to generate electricity only mattered for the first 20 years of electricity adoption, while after 1900 most locations were quickly connected to large waterpower plants by long-distance transmission lines. The clear dominance of waterpower plants in electricity generation only ended with the emergence of nuclearpower plants in the 1960s with current production almost equally split between the two (Weingartner 2016).

C.2 The technological revolution: Chemistry and education

Landes (1969) describes the second industrial revolution as characterized by major advances in electrical and chemical sciences and a shift away from early-modernising sectors such as cotton textiles. The development of the chemicals industry was highly dependent on the commercial adoption of electricity itself. This was due to new methods in chemistry requiring high amounts of electricity, for example the electrochemical production of calcium carbide developed at the end of the 19th century.[64] This is reflected in the chemical sector being one of the main producers and consumers of electricity at the start of the 20th century (accounting for a quarter of all energy generated from waterpower, see Department des Inneren 1891-1920).

The development of the chemical industry in Switzerland did not receive direct support by the state or protection (Homburg et al. 1998). However, there was crucial cooperation between government and industry in education and research. For example, the Swiss

[64] The importance of electrochemistry can hardly be understated for the Swiss chemical industries, but it should be noted that even before 1880 there existed chemical plants focussing mainly on the production of synthetic dyes with alizarin (red) being the main product (Homburg et al. 1998). These chemical plants established themself close to the pre-existent local textile industries, especially in Basel. Another advantage was that Switzerland had no patent-law till 1907 allowing the imitation and improvement of dyes already patented abroad (see "Chemische Industrie" in HLS 2020). However, many of the initial chemical companies producing basic and intermediate products disappeared with the spread of the railway as transportation costs went down and larger foreign plants started supplying the local industry (Homburg et al. 1998).

Federal Institute of Technology (today ETH) founded in 1854 provided teaching and research laboratories imitating the German model. These institutes provided expertise in the application and development of chemical processes directly or through graduates to the chemical industry. It also led to the development of new occupations, for example that of the well-paid industrial chemists developing new chemical processes outside of academia (Homburg et al. 1998).

The underlying educational changes were much broader than just at the tertiary level. For example, as industrialization increased chemistry teaching had become well established in US secondary schools, including laboratory work, in the late 19th century (Fisher 1986). Switzerland saw similar developments in providing practical industrial-technical knowledge at the secondary school level, for example through cantonal industry-schools (Gonon 1997). These changes did not just occur with regards to the chemical industry rather the dual education system in Switzerland in the late 19th century more broadly started to focus on providing also theoretical rather than just practical knowledge as the demand for a more skilled workforce increased (Wettstein 1987). For example, in 1887 a Bernese politician bemoaned in a parliamentary motion the lack of technically well educated workers (especially in mid-level roles), which was followed by the opening of new polytechnic universities ("Technikums") in short successions during the 1890s to provide this type of education (see "Technikum" in HLS 2020). Vocational schools (secondary level) and technical colleges (tertiary level) that started to become more widespread during the end of the 19th century still remain a key part of the educational system in Switzerland providing both job-specific practical skills and more broad theoretical knowledge (see Wettstein 1987; Mägli 1989; Halbeisen et al. 2017). These new schools were often initially financed by employers, employer-, and employee-associations or municipalities, while the central government started to play a more important role only later on (see "Berufsbildung" in HLS 2020).