The long-run gains from the early adoption of electricity *

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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 initial impact of new technologies within advanced countries has been illusive. Resolving this puzzle, this paper documents that the early adoption of electricity across 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, this paper finds that electricity adoption at the end of the 19th century led to structural transformation. However, economic development did not converge across areas in spite of the expansion of the electricity grid making access to electricity universal in the early 20th century. Instead, areas which adopted electricity early continue to be more industrialized and have higher incomes today. In particular, the geographical distribution of the newly emerging chemical industry was shaped by early electricity adoption, while employment gains through the building and operation of new power plants were mostly short-lived. The main mechanism through which differences in economic development persist in the long-run is through increased human capital accumulation and innovation, rather than persistent differences in the way electricity is used.

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1 Introduction

The adoption of new technologies is seen as being at the core of economic development. The timing and intensity of adoption is associated with a drastic divergence in incomes across countries (see e.g. Bernard & Jones 1996; Comin & Hobijn 2010; Comin & Mestieri 2018). Despite this apparent importance of the early adoption of new technologies, its effect within advanced countries remains illusive.[1] Many major technological breakthroughs, like electricity and information technology, that became universally adopted and had an important economic impact later on, initially diffused slowly and did not appear to have had an immediate positive economic effect (see e.g. Mansfield 1961; David 1990; Jovanovic & Rousseau 2005; Hall & Rosenberg 2010).[2]

This raises the question whether the pattern in which new technologies diffuse across advanced economies 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).

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 initial adoption of a new technology led to contemporaneous economic development,[3] (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 examine these three questions empirically in the context of the early commercial use of electricity across late 19th century Switzerland. Electricity is a particularly well suited technology to answer these three questions. Usually, the adoption of new technologies is confounded by being embodied in equipment with the need for physical capital accumulation on-site, this equipment might subsequently become obsolete, but prevent the

[1]Recent empirical studies have started to look at the long-run impact of technology adoption within countries at the peak of their importance. While Lewis & Severnini (2019) find some positive lasting effect of rural electrification in the US during the 1930s on agriculture and sub-urban exapnsion, Franck & Galor (2019) finds that areas that most intensively had adopted steam engines during the 1860s in France are poorer today.

[2]Most is known about the way new technologies are adopted in agriculture expanding on seminal work by Foster & Rosenzweig (1995), but a set of papers recently started to also evaluate technology adoption in manufacturing (see Bloom et al. 2013; Atkin et al. 2017; Giorcelli 2019; Juhász et al. 2019).

[3]The effect of the adoption of new technologies in historic settings at relatively early stages has of course been documented before. For example, De Pleijt et al. (2018) looks at the effect the adoption of the steam engine across England by 1800, only about 30 years after James Watt's considerable improvements to its design. However, what my paper is able to contribute here is that it looks at a particularly brief and well defined window of less than 20 years since the first commercial usage of the new technology. This represents a particularly brief time-window when considering the slow speed of adoption of new technologies in the 19th century. Specifically, I will focus on electricity adoption by 1900, which had only started to disseminate with its earliest relevant economic application dated between 1882 and 1894 (see Jovanovic & Rousseau 2005; Comin & Hobijn 2010).

adoption of newer technologies (see Boucekkine et al. 2008 for a summary).[4] Electricity is different as its usage does not necessarily require large investments on-site, as energy can be drawn as needed from a network even by small firms using varied types of machinery (Mokyr 2010). This also meant that after a slow initial adoption due to limitations in the available transmission technology, its use became quickly widespread in advanced countries as transmission technologies improved and the electricity grid expanded.

Late 19th century Switzerland provides an advantageous historic setting to evaluate the early adoption of electricity.[5] First, the country was at the forefront of electricity adoption at the time. 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 on local waterpower for electricity generation.[6] Third, the differential exposure to electricity was only short-lived as after 1900 long-distance transmission was implemented, which made locally generated electricity available in other parts 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.

I find that the initial round of electricity adoption had a considerable effect on structural transformation. Locations that adopted electricity early experienced a contemporaneous fall in agricultural employment and an increase in manufacturing employment. I also find that despite the rapid expansion of the electricity grid in the early 20th century, areas that had adopted electricity earlier continued to be more industrialized over 100 years later. The earlier adoption of electricity did not just increase the level of industrialization. Manufacturing employment continued to diverge between areas which adopted electricity early and those which did not throughout the first half of the 20th century. This lasting positive effect on economic development is also reflected in higher median incomes today. Finally, I find evidence that earlier exposure to electricity led to an immediate increase in human capital accumulation and innovation activity.[7] This in turn appears to have been the main driver of subsequent economic growth. Importantly, this is in contrast

[4]For example, steam-power required the costly installation of boilers, engines, shafting, and belts throughout a factory and complementary skilled workers operating the equipment to provide energy (Du Boff 1967). This specialization potentially leads to technological hysteresis and a slow-down in the development of new technologies and industries (see e.g. Brezis & Krugman 1997; Franck & Galor 2019).

[5]I use the following terminology here: Adoption of electricity refers to both the generation and use of electricity, where within geographical areas the later was dependent on the former during the early phase of adoption. In contrast, when I refer to generation or use of electricity individually, this refers explicitly to this specific aspect of the adoption of electricity. In addition, access to electricity refers to the possibility to use electrical power through having been connected to the emerging electrical grid.

[6]Note that, electricity from thermal power was not an economically feasible option on a large scale in Switzerland at the time due to (i) low thermodynamic efficiency in electricity generation and (ii) the high cost of imported coal (Bossard 1916). So that the vast majority of electricity generated was from waterpower until the building of nuclearpower plants in the 1960s (Weingartner 2016).

[7]This documented increase in human capital reflects an improvement in education of the local population with there being no evidence of increased in-migration.

to the usage of electricity itself, where there is no evidence of persistent differences across areas after access became universal through the extension of the electricity grid.

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 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 in the early 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).[8]

The key challenge in studying the effect of technological change, and particularly its early adoption, is that the decision to adopt is not random. Rather the most advanced areas and the ones that have most to gain are likely to adopt a new technology first. This means any observed effect might potentially reflect underlying local advantages, e.g. human capital, institutions or culture. These factors seem well suited as an explanation for why differences in prosperity across areas persist even as technologies become obsolete or universally adopted. This issue appears of particular concern when looking at technology adoption across countries, where differences in the timing and intensity of technology adoption are documented to have the largest and most permanent impact. Accordingly, well identified micro-level evidence on early adoption of new technologies is crucial to understand what drives long-run differences in economic development.

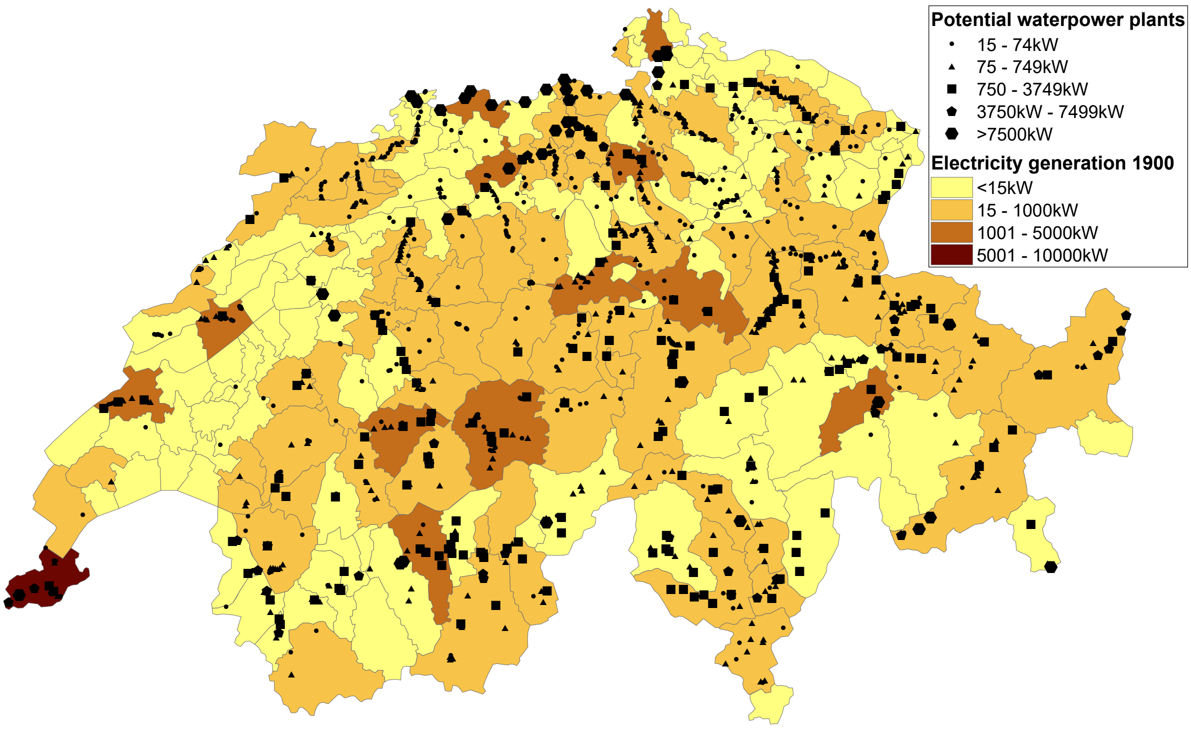
Ideally, assessing the causal impact of early technology adoption requires an environment where: (a) adoption was initially as good as random, and (b) those initial differences only mattered for a short period. Switzerland's adoption of electricity in the late 19th century provides a unique setting, in which both these requirements are met. First, the country was poor in natural resources, which meant that the only economically viable way to generate electricity was to use waterpower. Importantly, this suitability of areas to generate electricity was based almost entirely on small local geographical variations (e.g. the gradient of a river). 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 waterpower plants.[9] As it can be clearly seen, the number of available locations and their potential is crucial for the observed electricity generation

[8]The data used is based on district level tables compiled in the original publications by the Swiss census bureau. No individual census records are available. The censuses are conducted about 8-12 years apart and not in all years the information is compiled in the required way. I newly digitized district-level information on sectoral employment for roughly every 20 years during the period 1860-2011.

[9]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).

by 1900. Second, these geographical features only mattered for the use of electricity for the initial 20 year period from 1880 till 1900,[10] as in this period, electricity had to be consumed near to the power source as transmission over long distances was uneconomical. From 1900 onwards this constraint was relaxed as long distance transmission lines were established from where electricity was most efficiently produced to wherever there was demand.[11] 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.

Figure 1: Electricity generation in 1900 and potential waterpower plants



Notes: The figure depicts electricity generation in kW from waterpower across Swiss districts in 1900. Black points represent all potential locations for waterpower plants of more than 15kW generation. The size and shape of the point corresponds to the location and kW generation of optimally located potential waterpower plants: (i) 15-74kW, (ii) 75-749kW, (iii) 750-3750kW, (iv) above 3750-7499kW and (v) above 7500kW (these groups correspond to historically used groups measured in HP with 1HP=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). More detail is provided in Section 3 and Data Appendix C.1.

I use variation in the suitability to produce electricity from waterpower across areas, that occurs due to otherwise unimportant geographical differences, to instrument the ac-

[10]Geographical features still continued to be relevant for electricity generation, however I'm able to directly observe any further extension of local electricity generation that occurred after the initial 20 years to distinguish this later extensions from the initial adoption of electricity.

[11]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).

tual adoption of electricity. I call this the potential to generate electricity. The suitability of my instrument relies on two assumptions: First, the potential to generate electricity had to be as good as randomly assigned across areas. This appears to be the case as areas with and without potential electricity generation did not differ in industrialization or population density before the adoption of electricity.[12] Second, the exclusion restriction needs to hold, which means that the potential to generate electricity only affected economic development through electricity adoption. This also appears to be the case as the potential to generate electricity did not lead to economic development before the commercial adoption of electricity. Further, there is no relationship between the potential for electricity generation and the mechanical energy generated by watermills in 1880.[13]

An additional concern that emerges in the long-run is that the same geographic features are likely to remain relevant for the building of waterpower plants even after 1900. While the location of these plants are no longer important for the local use of electricity due to the extension of the supply network, they might still have a direct impact on economic development through construction and operation. I account for this by separately controlling for the building of plants after 1900. In this way, I disentangle the long-run effect of the adoption of electricity in between 1880-1900 from the effect of subsequent power-plant construction which might be correlated with the instrument.

My claim is that the observed divergence in economic development emerged solely due to a brief period in which electricity adoption differed across areas. However, the effect of early electricity adoption can be even further distinguished into the effect of its use and its generation. Electricity is well suited to distinguish these effects, as electricity generation and distribution emerged as distinct industries.[14] Interestingly, I find that electricity usage rather than generation is the main route through which early electricity adoption affected economic development in the long-run. While in the short-run industries associated with the generation and use of electricity both experienced considerable employment growth, in the long-run the employment gains in industries associated with electricity generation declined.[15] In contrast, employment in industries exclusively using electricity

[12] Appendix Figure A.1 provides additional descriptive maps.

[13] Watermills here refers to all energy generated from water that is exclusively transmitted via mechanical means, i.e. wheels, shafts, gears, and belts, and was not converted into electrical energy. It might appear surprising that mechanical power generation is not related to the potential to generate electricity, however this is for the simple reason that the materials used for mechanical transmission of energy were unable to transmit the considerable amounts of energy that waterpower could provide and also required that location of generation and use were in immediate proximity. See for example Du Boff (1967) on the crucial differences between mechanical and electrical power generation, transmission and use.

[14] This clear distinction in generation and use of electricity is for example different from steam power which was not only used in many factories, but required the installation of steam engines and skilled workers maintaining them within the same factory (see Nye 1992; Goldin & Katz 1998; De Pleijt et al. 2018).

[15] The employment growth associated with electricity generation in the short-run was mostly through industries associated with the construction of waterpower plants. These employment gains disappeared after 1900. In contrast, employment in electricity generation continued to persist and even expanded

further expanded in areas that had adopted electricity early. In particular, employment in chemical industries, where electricity was a crucial input in novel production processes, continued to expand even after 1900. Indeed, more than 70% of the modern-day spatial distribution of chemical industries can be explained by the early adoption of electricity.

Why did a 20-year period of early exposure to electricity have such important consequences on economic development? My preferred explanation is that earlier exposure triggered the accumulation of human capital and further innovation. In turn, this is what leads to the persistent differences in economic development. I find evidence that those areas which adopted electricity early immediately experienced improvements in educational outcomes. In particular, understanding of maths and general knowledge at the secondary level of schooling increased drastically, while literacy and other knowledge at the primary level of schooling improved little. One of the drivers for this increase in educational outcomes was the dual education system. I find evidence that both the number of institutions and students expanded more quickly in areas which adopted electricity earlier. For this, the cooperation of employers and local governments was crucial in the provision of knowledge through apprenticeships, industry- and technical-schools, which increasingly focused on providing theoretical rather than practical knowledge in the late 19th century as the need for an evermore skilled workforce increased (Wettstein 1987). The increased local importance of education is also underlined by increased support in national referendums for more central government investment in education. Crucially, these differences in the level of human capital that emerged at the end of the 19th century persist up to the present day: areas exposed earlier to electricity still have a higher share of secondary and tertiary educated individuals by 2010.

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 by 1929 between areas which adopted electricity early and those that did not. This highlights that differences in economic development from early exposure to electricity persisted even as access and utilisation of universal became universal across Switzerland due to the extension of the electricity grid.

The initial geographic constraints on the early adoption of electricity in Switzerland meant that remote areas were heavily exposed to the new technology, rather than just urban centres, where new technologies are usually first adopted. How did high levels of human capital and innovation persist in this rather unusual setting? I find empirical evidence that the infrastructure network adjusted and in fact the Swiss rail network remains more dense, in terms of connections and passengers, in areas which had adopted electricity earlier.[16] This is further underlined by higher support for government infras-

further after 1900. However, the economic magnitude of these employment gains are small throughout in comparison to the ones in industries that exclusively used electricity.

[16] That persistent differences in economic development from the early adoption of electricity are associated with human capital accumulation and changes to the infrastructure network appears a surprising

tructure investment emerging after 1900 in these areas. This complementary change in the infrastructure network providing improved access to distant markets and knowledge helps explain how areas that had adopted electricity early were able to retain specialized industries and continue to innovate despite, in many cases, being rather remote and having a small population.

My paper contributes to several strands of the literature. First, several papers have studied the spread of electrification in developed countries in the first half of the 20th century (Kitchens 2014; Kitchens & Fishback 2015; Gaggl et al. 2019; Lewis & Severnini 2019; Molinder et al. 2019; Leknes & Modalsli 2020).[17] The main innovation of this paper is to study the initial adoption of electricity at the end of the 19th century and its long-lasting effect.[18] Looking at this early adoption is important as electricity has long been seen as one of the key technologies of the second industrial revolution (see e.g. Mokyr 1992), but, its impact on manufacturing between 1870-1914 has not been thoroughly analysed. 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.[19] My paper finds a considerable impact of electricity on industrialization as early as 1900. I am also able to separately investigate the role of electricity generation and use. In particular, the early use of electricity explains where the chemical industry developed across Switzerland. This underlines the crucial role electricity played in facilitating new production processes in other emerging industries during the second industrial revolution.

Second, my paper contributes to a literature emphasising 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 (see e.g. Galor & Moav 2006; Galor 2011; De Pleijt et al. 2018), and in turn on whether human capital is a main driver of economic growth (see e.g. Lucas 1988; Romer 1990). Notably, the switch from steam engines to electricity as a power source represents a drastic break point in the process of industrialization, which even changed the layout of factories (Du Boff 1967). My paper

parallel to recent findings by Dell & Olken (2020) on the positive long-run effect of the economic changes implemented by the Dutch Cultivation System on economic development across Indonesia today. Also with the crucial distinction that the change in the economic structures in Switzerland occurred naturally due to a change in technology rather than being imposed.

[17] A corresponding literature look at the effect of electrification in developing countries in the second half of the 20th century, for example Dinkelman (2011), Rud (2012), Lipscomb et al. (2013), Van de Walle et al. (2017), de Faria et al. (2017), Moneke (2019), Lee et al. (2020).

[18] To the best of my knowledge, the study with the earliest starting point so far is Leknes & Modalsli (2020). They study the adoption of electricity across rural Norway between 1891 and 1920. However, they explicitly treat the period 1891-1900 as the pre-electricity period for rural Norway (as in less than 2% of their sample a hydroelectric plant existed or was being build by 1900). The other papers focus on 1900-1920 (Molinder et al. 2019), 1910-1940 (Gaggl et al. 2019), 1929-1955 (Kitchens 2014), 1930-1960 (Lewis & Severnini 2019), 1935-1940 (Kitchens & Fishback 2015).

[19] Juhász et al. (2019) document that the initial adoption of a new technology can be rather tumultuous for mechanized cotton spinning in early 19th century France.

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.[20] These differences persisted with the early adopters of electricity continuing to exhibit higher levels of education and innovation today. This also appears to be the main driver of subsequent economic development, providing new insight on the contribution of electricity to fostering skill biased economic growth from the late 19th century.

Finally, my paper contributes to a literature trying to explain persistent differences in the spatial distribution of economic activity. The seminal study of Davis & Weinstein (2002) highlights that 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. Most closely related to my work here is a small set of papers which has studied the long-run impact of the adoption of specific technologies. Juhász (2018) shows that areas in France which adopted mechanized cotton spinning during the Napoleonic Blockade continued to be more specialized in spinning and had higher incomes for several decades, while Franck & Galor (2019) 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. 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 considerable 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 developed countries.[21] However, what these papers have in common is that they look at the later-stages of a technology's adoption at the height of its importance rather than the pioneering adoption of a new technology during its infancy.[22] My paper finds that areas that adopted electricity early continued to be more industrialized and have higher incomes even 100 years later. This is despite electricity adoption having differed across areas for only a short period of time (of about 20 years). I also provide evidence that the mechanism explaining this lasting effect is increased human capital accumulation and innovation in areas with early electricity adoption, which fostered further

[20]In general, the consensus is that technical change in the 20th century has favoured skilled workers (see e.g. Goldin & Katz 1998; Acemoglu 2002).In contrast, the impact of technical change throughout the 19th century is generally viewed as overall leading to deskilling and lower levels of human capital accumulation, even though recent empirical evidence provides a somewhat more nuanced picture (see Goldin & Sokoloff 1982; Atack et al. 2004; Katz & Margo 2014; Franck & Galor 2019; De Pleijt et al. 2018).

[21]In contrast, the literature using cross-country variation in timing and intensity of adoption of new technologies finds large persistent effects for a vast variety of technologies, see e.g. Comin & Hobijn (2010), Comin & Mestieri (2018), Gollin et al. (2018). These findings correspond well to Figure A.3 in the appendix, which shows a drastic persistent growth in per capita incomes in Switzerland, which was the largest initial adopter of electricity in the world till the 1900s, from around 1885 onwards.

[22]Another potential explanation for differences disappearing in the long-run is that this reflects considerable economic spillovers, e.g. through trade or migration, as well as government redistribution across areas, which attenuates the effect of the local adoption of technology within countries in the long-run.

economic growth. Notably, as electricity became more widely used as a technology there no longer are any observable differences in its use as early as 1929 across areas.

The remainder of my paper is organised as follows. Section 2 discusses the historical context of electrification and the second industrial revolution. 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.

2 Historical Context

2.1 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.[23] 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),[24] just in front of the United States (81.7 kWh in 1902; 125.2 kWh in 1907).[25]

A key feature of Swiss electrification was its heavy reliance on waterpower due to the absence of fossil fuel 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

[23]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).

[24]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.

[25]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).

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 (see Appendix Figure A.2). The gradient of a river segment combined with complementary features like river bends or bifurcations were crucial in determining the amount of electricity that could be generated at a site (see Bossard 1916, Volume 4, p.15-16). This reliance on waterpower is also recorded in the Swiss statistical yearbook, which estimates that more than 99% of electricity produced was from waterpower plants by 1920 (see Data Appendix C.1 for more detail).

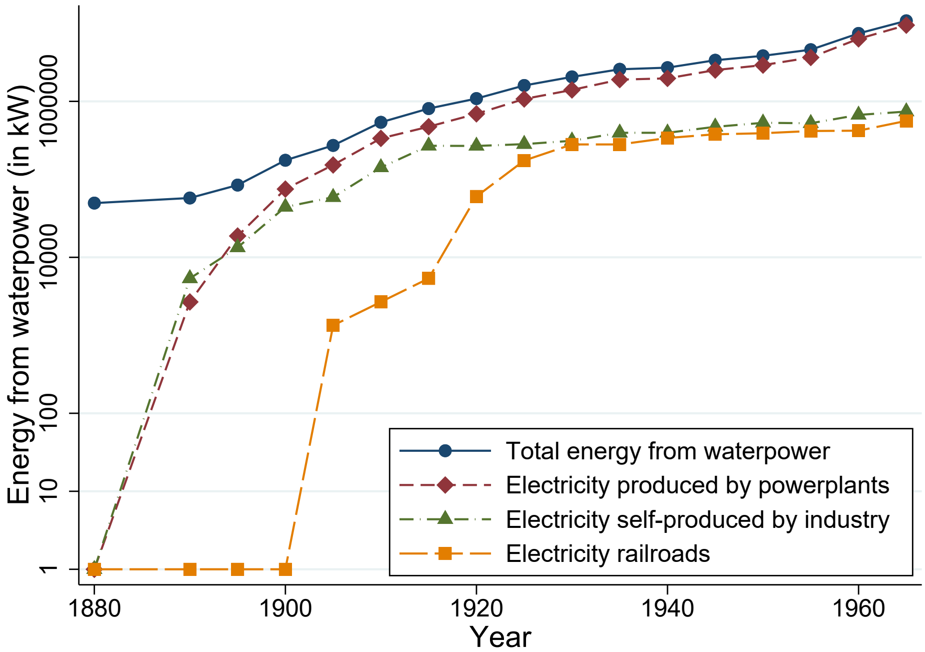
Interestingly, waterpower was not just crucial for electricity generation in Switzerland, but the development of electric power generation and transmission was in return crucial in allowing the exploitation of the available waterpower potential. This was due to mechanical energy generation and transmission by watermills having being only 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. 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). 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 2).[26] 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.[27] Figure 2 highlights this continuously increasing role of power-plants built solely for supplying electricity to consumers. 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 electric-

[26]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).

[27]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).

Figure 2: Electricity generation by source 1880-1965



Notes: Energy produced from waterpower in kW from 1880 to 1965. Electrical power produced is separated into the electricity produced by power stations producing general supply, electricity produced by industrial plants primarily for on-site usage as well as power plants used for the electrification of the Swiss railroads. The difference between all energy generated from waterpower and electricity generated reflects the energy generated by watermills, which was transmitted exclusively by mechanical means. This equal to total energy produced in 1880 and remains stable till 1930. Source: Kammerer et al. 2012.

ity 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.[28] In a similar way, in cases where power-plants had 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

[28]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).

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).

2.2 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.[29] 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 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

[29] 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).

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 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).

2.3 A historical example: The story of Lonza

Many Swiss chemical firms established at the end of the 19th century relied on the availability of cheap electricity (see e.g. Lunge 1901).[30] It seems illustrative to discuss the story of one of them in more detail. I choose Lonza as its name is based on the local river used to power the electrical generators.

Lonza was founded in 1897 in the small municipality of Gampel (population of 421 in 1880) with its own waterpower plant producing electricity to manufacture chemicals, in particular calcium carbide. The production of calcium carbide requires a large amount of energy and has not changed since its invention in 1892. For this purpose, Lonza operated two waterpower plants in Gampel with an average electricity generation of 1725kW and 3750kW built in 1898 and 1900 (see Bossard 1916). Local employment in chemical industries tripled from 5 in 1880 to 14 in 1900. Lonza quickly outgrew Gampel in the following years and opened an additional production site in the neighbouring municipality of Visp (11.9km away) in 1909 extending production to synthetic fertilisers, vitamins, acids,chemical intermediates and additives.[31] Lonza's production was mainly not destined for the local market and while a railway line to Geneva already existed in 1880,

[30]For example, AIAG (aluminium 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).

[31]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

the opening of the nearby Lötschberg Tunnel in 1913 connected the Lonza plants directly with Central Switzerland (and through this to Germany). 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 with the Visp-site being the largest production and research site with 2800 employees. Gampel, where the initial carbide oven was closed in 1964, also 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).

The emergence of Lonza, and the chemical industry more generally, created new educational opportunities. This is for example illustrated by Paul Hermann Müller (son of a railroad employee), who was born in Olten in 1899. He started to work as a laboratory assistant at Dreyfus & Cie. in 1916 after dropping out of secondary school due to bad marks. He than joined Lonza as an assistant chemist in their industrial laboratory of their electrical plant. There he acquired a wealth of practical knowledge which later stood him in good stead in his career as an industrial chemist (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. He than returned to work in the private sector starting his career with Geigy in Basel, working initially on vegetable dyes and natural tanning agents, moving to work on insecticides later on. He received the 1948 Nobel in Physiology or Medicine prize for his work on the synthesis of DDT, an important chemical compound in the eradication of malaria across the world. Again this provides only an example, but it helps to highlight the crucial interplay between the nascent chemical industry, education and individual careers.

These are only examples of how the adoption of electricity at the end of the 19th century transformed two rather small municipalities and individual opportunities drastically. However, as will be shown in Section 4 these are not only individual success stories, but rather were common across Switzerland.

3 Empirical Strategy

This section describes the empirical strategy and briefly summarizes the main data used. More detailed information on my data sources is provided in the Data Appendix C.

What was the effect of the early adoption of electricity on economic development? To answer this question, I explore the empirical relationship between the district-level increase in the supply of electricity and indicators of development, while controlling for confounding factors.

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.

Swiss districts ("Bezirke"), the administrative level directly 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 labour markets up to the middle of the 20th century.[32] 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. The measure $\Delta E_{d,1900-1880}$ captures electricity adoption in kW per person in each district between 1880 and 1900.[33] Crucially, electricity in Switzerland was nearly exclusively generated from waterpower and due to technological constraints was not yet supplied over long distances. Accordingly, this measure of electricity adoption reflects both the effect of local generation and use of electricity.

I estimate the following equation to capture the contemporaneous effect of the adoption of electricity on outcomes measuring 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 a measure of economic development with d denoting district and 1900-1880 representing the time-period. I use alternative outcomes, but a particular focus is placed on the structural transformation from agriculture into manufacturing and service employment. These represent crucial measures of economic development as historically areas became rich through labour moving from agriculture into modern activities with higher productivity and productivity growth (see e.g. Kuznets 1957; Kuznets 1973; Gollin et al. 2014). $X_{d,1880}$ 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 both demand- and supply-side consideration. On the one hand, economic development potentially creates an upward

[32] 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 sizeable geographic distinction between place of living and work only emerged with the building of motorways and mass motorisation 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).

[33] The measure is in kW (kilowatt) 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.

bias through increasing local demand for electricity generation. 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 situations can create obstacles for the exploitation of the full waterpower potential for electricity generation (Bossard 1916).

To address the potential endogeneity of electricity adoption, I use the following First-Stage regression:

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

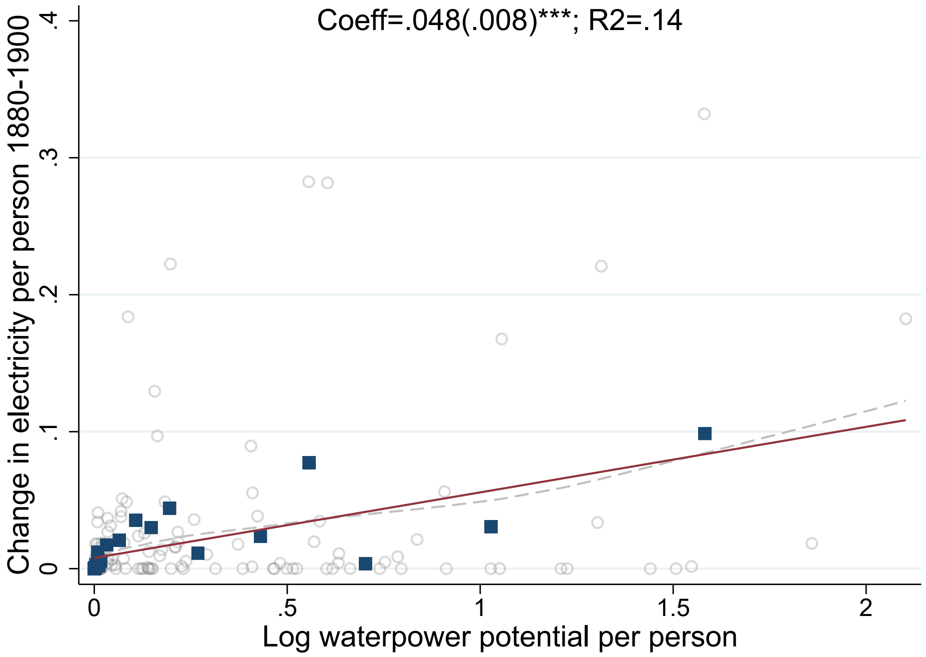
where the increase in the production of electricity between 1880 and 1900 is instrumented by the log potential for energy produced from waterpower per person in 1880, denoted $\log P_d$.[34] The waterpower potential is based on a detailed plan — devised by engineers at the time — of all existing and potential waterpower plants and the energy they could generate (see Bossard 1916). 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 existing obstructions that could inhibit the building of potential waterpower plants, and ii) any economic considerations for the operation of potential waterpower plants (see Bossard 1916, Volume 5, p.9-16). In addition, the study aims to this provide information on the optimal network of potential waterpower plants, taking into account the effect of each potential waterpower plants on the other potential waterpower plants in the network, rather than just individually treating each potential waterpower plant as an individual entity. Figure 3 highlights the relationship between the increase in electricity produced between 1880-1900 and the waterpower potential per person across districts.

The potential electricity generation, in contrast to the actual electricity generation, is not associated with a higher level of economic development across districts by 1880 (see Appendix Table B.1).[35] Appendix Figure A.1 provides additional descriptive maps for electricity adoption and development across Switzerland. That the waterpower potential was relevant for economic development only through electricity generation is further supported by Figure 4. It shows that the waterpower potential is a strong predictor of the change in electricity produced across districts between 1880-1900 (left-panel), but it is not relevant for the energy generated by watermills, using only mechanical power generation and transmission, in 1880 (right-panel). The later might appear surprising at

[34]For simplicity I refer to the transformation as the log while the exact transformation used is the inverse hyperbolic sin 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 that the marginal gain from electricity adoption is decreasing. Results are robust to using potential for energy produced from waterpower per person as the instrument with results displaying slightly wider confidence intervals.

[35]The potential electricity generation across districts is only associated with some major geographical differences. 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).

Figure 3: First-stage relationship

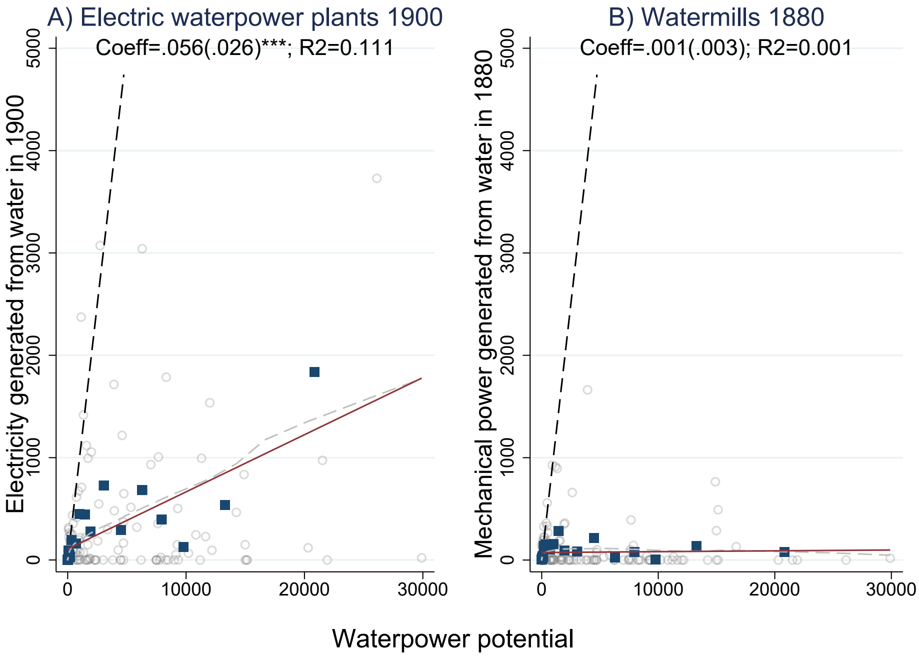


Notes: The binned scatter plot illustrates the relationship as described in Equation 3 between the log waterpower potential per person and the change in electricity produced from waterpower between 1880 and 1900 across districts. Blue squares represent the binned observations with the solid red line being the linear fit. In the background hollow grey dots correspond to the underlying observations and the dashed grey line represents the locally weighted fit. N=178 in 20 bins.

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 and also reflects that location of generation and use had to be located in immediate proximity further complicating the exploitation of the full waterpower potential before 1880 (see e.g. Du Boff 1967).[36] Accordingly, this means that the technologies available before electricity were unable to fully exploit the potential waterpower. This suggests that the specific geographic features relevant for electricity generation were otherwise economically irrelevant, including power generation in any other way, supporting the validity of the exclusion restriction. To even further alleviate any concerns, I will later also present estimates based on Equation 2 for the period 1860-1880, which show that the early adoption of electricity 1880-1900 is unable to predict any economic development in this pre-period.

[36]Most of the watermills in 1880 are watermills are used for milling flower or sowing wood that rarely generated more than 75kW (100PS) of energy and were initially build as far back as the middle ages. In comparison the majority of electric power plants generated vastly more energy than 75kW (see Apendix Figure A.2.)

Figure 4: Electric- versus mechanical-power generated from potential



Notes: The binned scatter plots illustrate the relationship between the total waterpower potential in kW of a district and (i) electricity generation from waterpower by 1900 and (ii) the energy generated by watermills using exclusively mechanical power transmission by 1880 across districts. The x-axis give the potential kW from waterpower (based on the lowest water level during the year), while the y-axis gives the actual average kW of energy generated throughout the year. Blue squares represent the binned observations with the solid red line being the linear fit. In the background hollow grey dots correspond to the underlying observations and the dashed grey line represents the locally weighted fit. The blacked dashed line provides a 45-degree line of full exploitation of the minimum potential throughout the year. Some districts actual electricity generation is slightly above the 45-degree line because it varies with the water level throughout the year, i.e. turbines have been installed that operate at less than full capacity in parts of the year when the water level is low. Geneva with an electricity generation of 9900kW and a potential of 16785kW lays outside of the depicted range in the left figure. N=178 in 20 bins.

Next I study whether the contemporaneous effect persists in the long run: I analyse 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 as in Equation 2, but where t 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.[37] 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 unlikely to be influenced by this due to the development of long-distance transmission grids, this variable accounts for the potential correlation between the instrument and economic activity due to the construction and operation of waterpower plants for electricity generation that occurs after 1900.[38]

Information on electricity generation across Switzerland between 1880-1900 comes from "The waterpower of Switzerland in 1914" (see Bossard 1916).[39] 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. The same source also provides information on location and energy generation for all potential waterpower plants that could be build across Switzerland to maximise electricity generation at the time. From this, I calculate the electricity generation and potential electricity generation at the district level. Panel A in Table 1, which presents summary statistics for the main variables, highlights that the average electricity 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 electricity generation from waterpower up to 2018. More detailed information on the electricity data is provided in Data Appendix C.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 focussing on the years 1860, 1880, 1900, 1920, 1941, 1955, 1965, 1975, 1985 and 2011

[37] 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.

[38] Consequently, my main variable of interest captures the causal effect of electricity adoption 1880-1900, while disentangling it from any later increase in electricity generation after 1900. In the case of not controlling for $\Delta E_{d,t-1900}$ the effect should rather be interpreted as the overall effect of electricity adoption from 1880 up to point t. In Appendix Figure A.6 this result is presented, which compared to the baseline specification (presented in Figure 7) suggests that the effect of electricity on industrialization is even larger. In line with the extension of the electricity grid after 1900 this difference in coefficients is explained exclusively by an increase in employment in electricity generation after 1900 (see Appendix Table B.7). To avoid noise from pure improvements in technology over time leading to increase in electricity generation, e.g. more efficient turbines, I focus on the number of newly build waterpower plants as control instead of kW electricity generated after 1920.

[39] 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.

Table 1: 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

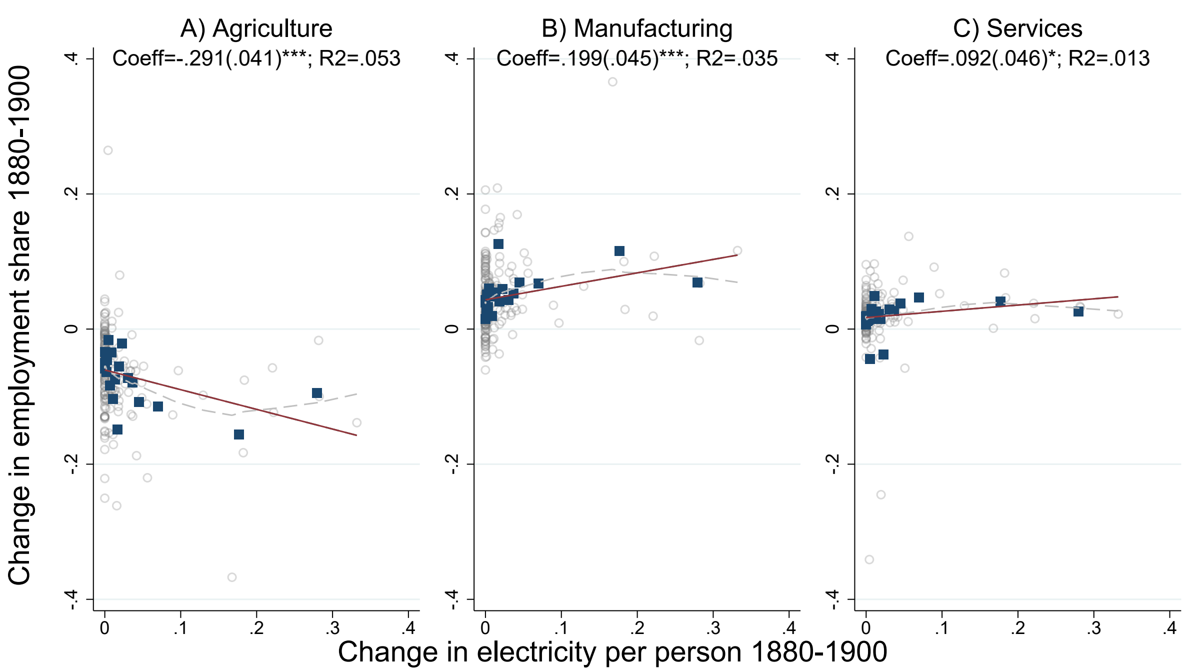
Notes: The table reports summary statistics for the main explanatory variables and main dependent variables. The columns report mean, standard deviation, 10th and 90th percentile and number of observations.

(see Bundesamt für Statistik 1860-2011).[40] These provide information on employment of individuals for the whole of the Swiss population at the district level. In addition, I also collect 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".[41] The category "Other" mainly comprises employment in mining, paper and typography. The additional breakdown by industries allows me to distinguish to which extend the effect of electricity adoption on manufacturing was due to electricity

[40] 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.

[41] 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.

Figure 5: Electricity adoption and structural change 1880-1900



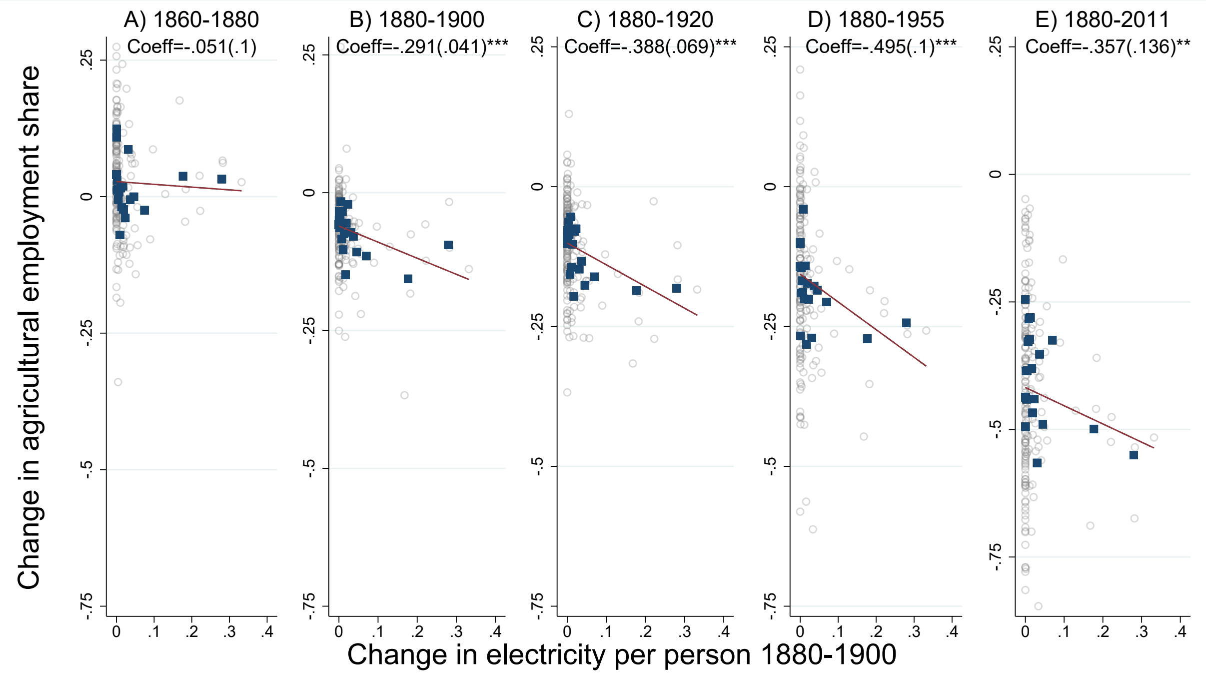
Notes: The binned scatter plots illustrate the correlation between the change in electricity generation 1880-1900 and change in share of employment 1880-1900 in a) agriculture, b) manufacturing, and c) services across districts. Blue squares represent the binned observations with the solid red line being the linear fit. In the background hollow grey dots correspond to the underlying observations and the dashed grey line represents the locally weighted fit. N=178 in 20 bins.

generation itself or rather due to the use of electricity. Additional information on the Census Data is provided in Data Appendix C.2.

Panel B-D in Table 1 highlights that by 1880 Switzerland was still a mainly agricultural economy, but that there was rapid structural change after 1880 with employment first transitioning from agriculture to manufacturing and then to services. Combining the data on electricity adoption and employment, Figure 5 visualizes the correlation between the change in the share of employment in (i) agriculture, (ii) manufacturing and (iii) services with the adoption of electricity in the short-run 1880-1900. The figure shows a substantial decrease in agricultural employment for districts with a higher electricity adoption and a corresponding increase in manufacturing and to a smaller extent services employment. Figure 6 illustrates that this structural transition is not just short-lived. Even by 2011, the early adoption of electricity continues to be correlated with a stronger decrease in the agricultural employment share since 1880.

These two main sources are complemented by a large set of other data sources measuring electricity use, education, innovation, and infrastructure over the long-run to evaluate the potential mechanisms for the persistent effect and a set of data sources to used to construct additional controls. Data Apendix C.3 presents the data-sources for these variables.

Figure 6: Electricity adoption and structural change in the long-run



Notes: The binned scatter plots illustrate the correlation between the change in electricity generation 1880-1900 and change in share of employment in agriculture for a) 1860-1880, b) 1880-1900, c) 1880-1920, d) 1880-1955 and e) 1880-2011 across districts. Blue squares represent the binned observations with the solid red line being the linear fit. In the background hollow grey dots correspond to the underlying observations. N=178 in 20 bins (N=177 in A) 1860-1880).

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 in the short-run. 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 use of electricity.

4.1 Short-run effect of electricity

Table 2 Panel A analyses the effect of the adoption of electricity between 1880-1900 on the change in the share of employment in agriculture 1880-1900.[42] This corresponds to

[42]Standard errors are clustered at the cantonal level due to their administrative importance within Switzerland (25 clusters). Similarly, sized standard errors are obtained clustering for spatially correlated error terms with a 35km kernal (see Conley 2008; Hsiang 2010). The kernal size is based on the longest electricity transmission distance in 1900.

the estimation strategy outlined in Equation 2. Column 1 corresponds to the bivariate regression plotted in the first panel of Figure 5, and shows a substantial decrease in agricultural employment for districts with a higher electricity adoption. In the next columns I introduce controls accounting for initial differences across districts that might be correlated with both the adoption of electricity and economic development between 1880-1900.

A first concern is that electricity generation might be correlated with major geographic differences across Switzerland. These might also affect economic development. To account for this, I add altitude, longitude and latitude as controls in the second column, which accounts for major differences in Swiss geography that occur in terms of elevation, from north to south, and from east to west. A higher altitude is related with less transition out of agriculture. The coefficients for longitude and latitude suggest that areas in the North-West (South-East) experience the lowest (highest) transition out of agriculture.

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 and crucial in the early stage of industrialization (Rosenberg 1972; Mokyr 1992). The previous use of waterpower 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. Consequently, the included control helps to disentangle any potential effect between the adoption of electricity after 1880 and any pre-existing usage of water as a power source.

A final concern is that there are region-specific unobservable in economic development which are correlated with electricity adoption. Accordingly, column 5 accounts for different trends in economic development across the seven major economic regions in Switzerland.[43] 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

[43] The 7 regions are Geneva-lake-region (Geneva, Vaud, Valais), Espace Mittelland (Bern, Fribourg, Jura, Neuchâtel, Solothurn), Northwestern Switzerland (Basel-City, Basel-Country, Aargau), Zürich (Zürich), Eastern Switzerland (Schaffhausen, Thurgau, St. Gallen, Appenzell Ausserrhoden, Appenzell Innerrhoden, Glarus), Central Switzerland (Lucerne, Uri, Schwyz, Obwalden, Nidwalden, Zug) and Tessin (Tessin) with the corresponding Cantons in brackets. These regions correspond to the European Unions NUTS-2 regions.

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.[44]

Appendix Table B.2 highlights that the coefficient is 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 (Squicciarini & Voigtländer 2015), religion (Becker & Woessmann 2009), culture (Alesina & Giuliano 2015) and institutions (Acemoglu et al. 2011). These factors appear at most of limited importance for the transition out of agriculture in Switzerland between 1880-1900. This is not necessarily surprising as their effect on future economic development is potentially already well accounted for by controlling for the level of economic activity observed in 1880 included in the baseline specification. In addition, the table shows that the result is robust to controlling for a vast set of additional geographic characteristics (cropland, presence of major rivers, average water-flow of rivers, bioregions, ruggedness). In particular, the share of available cropland and the Po-Basin bioregion are associated with less transition out of agriculture. However, these measures are based on modern data, as no historical information is available, so while it is reassuring that the effect of electricity appears robust to including them, they might provide bad controls as their measurement might be affected by the building of waterpower plants and later economic development.

Panel B of Table 2 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.[45] 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 columns (1)-(5). 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 already been allocated for purposes other than electricity generation and that legal ownership-rights were often unclear and difficult to resolve (see

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

[45]Appendix Table B.3 suggests that similar results are obtained using modern day potential for the building of small-scale waterpower plants in Switzerland using data from Schröder et al. (2012) as instrument. However, the predictive power of this instrument is considerably weaker and it's measurement is potentially endogenous to any dams and waterpower plants that have been build since 1880. In addition, it's explanatory power comes exclusively from its correlation with the historical instrument.

Table 2: Effect of electricity on agricultural employment 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)
	[-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)
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)

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 the share of employment in manufacturing and services as dependent variable, respectively. Robust standard errors in parentheses are clustered at the cantonal level. Square brackets present alternative Conley standard errors accounting for spatial correlation in Panel A and Anderson & Rubin weak instrument robust 90%-confidence intervals (under homoscedasticity) in Panel B. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Bossard 1916, Volume 4, p.7-8).[46] The -0.625 coefficient in column 5, obtained using the

[46]The city of Basel, the pre-eminent centre of the Swiss chemical-dye industry by 1880, provides an excellent illustration of the problem. Despite the considerable potential waterpower that the Rhine could

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.[47] 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 1), 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 2 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, so the partial equilibrium estimate 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 3 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 originating from the respective municipality, the canton, Switzerland or a foreign country does not change due to the adoption of electricity. This highlights that there appears to be little labour migration between 1880-1900[48] and that the observed employment growth is due to an increase in employment of the local

provide within the city to generate electricity and a plausibly large local demand for electricity, little was being exploited. The main users of waterpower continued to be an array of inefficiently small and fragmented watermills that in many cases date back to the middle ages (see Appendix Figure A.4). Electrification in Basel continued lagging behind until the city's main electric power plant with a generation of more than 2000kW was build in 1912 (Bossard 1916). Notably however, this relied on improvements in transmission technology, rather than a consolidation of ownership of local water-rights, as the power plant was located more than 10km away from Basel in the district of Liestal.

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

[48] By 1900, still the majority of the population was born in the municipality they currently lived in with the second largest group having been born in the same Canton, while migrants from other Cantons and immigrants were rare apart from in the larger cities (see "Binnenwanderung" in HLS 2020). Much more common appears to have been trans-Atlantic emigration, even though this was already declining at the end of the 19th century (see "Auswanderung" in HLS 2020).

Table 3: Effect of electricity on employment and population growth

	Employment growth 1880-1900			
	All	Agriculture	Manufacturing	Services
	(1)	(2)	(3)	(4)
Δ Electricity pp 1880-1900	1.242***	-0.553***	2.527**	1.203+
	(0.456)	(0.180)	(1.255)	(0.839)
	Population growth 1880-1900			
	Municipality	Canton	Swiss	Foreign
	(5)	(6)	(7)	(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 in 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. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

population.[49] This provides further evidence that the adoption of electricity led to local structural transformation through agricultural and surplus labour moving into manufacturing employment.

The crucial assumption for the IV results to be valid requires that the potential to produce electricity from waterpower affects employment shares 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 4 by replacing my dependent variables with the change in employment shares between 1860-1880.[50] There is no evidence that districts experienced a different pattern of development before electricity started to be adopted in the 1880s. No significant effect of the adoption of electricity 1880-1900 is observed on the change in the agricultural, manufacturing or services employment share 1860-80 without and with controls. The estimated coefficients even go in the opposite direction compared to Table 2 ruling out any pre-trends across districts that might drive the observed effect between 1880-1900.

[49]Male labour 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. In contrast, female labour force participation at the time is less than 50%. Appendix Table B.6 highlights that the initial employment growth 1880-1900 is mainly due to men finding employment, while later increases are due to female employment growth.

[50]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.

Table 4: Pre-trend analysis 1860-1880

	Agriculture		Manufacturing		Services	
	(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)
F-stat (1st stage)	36.17	17.46	36.17	17.46	36.17	17.46
Controls	No	Yes	No	Yes	No	Yes
N	177	177	177	177	177	177

Notes: The dependent variable is the change in the share of employment in agriculture, manufacturing and services between 1860 and 1880 as specified in the column header. This represents a period before the commercial adoption of electricity. The table analyses whether there is any correlation between the instrumented electricity adoption per person between 1880-1900 and pre-trend outcomes 1860-1880. Robust standard errors in parentheses are clustered at the cantonal level. 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. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

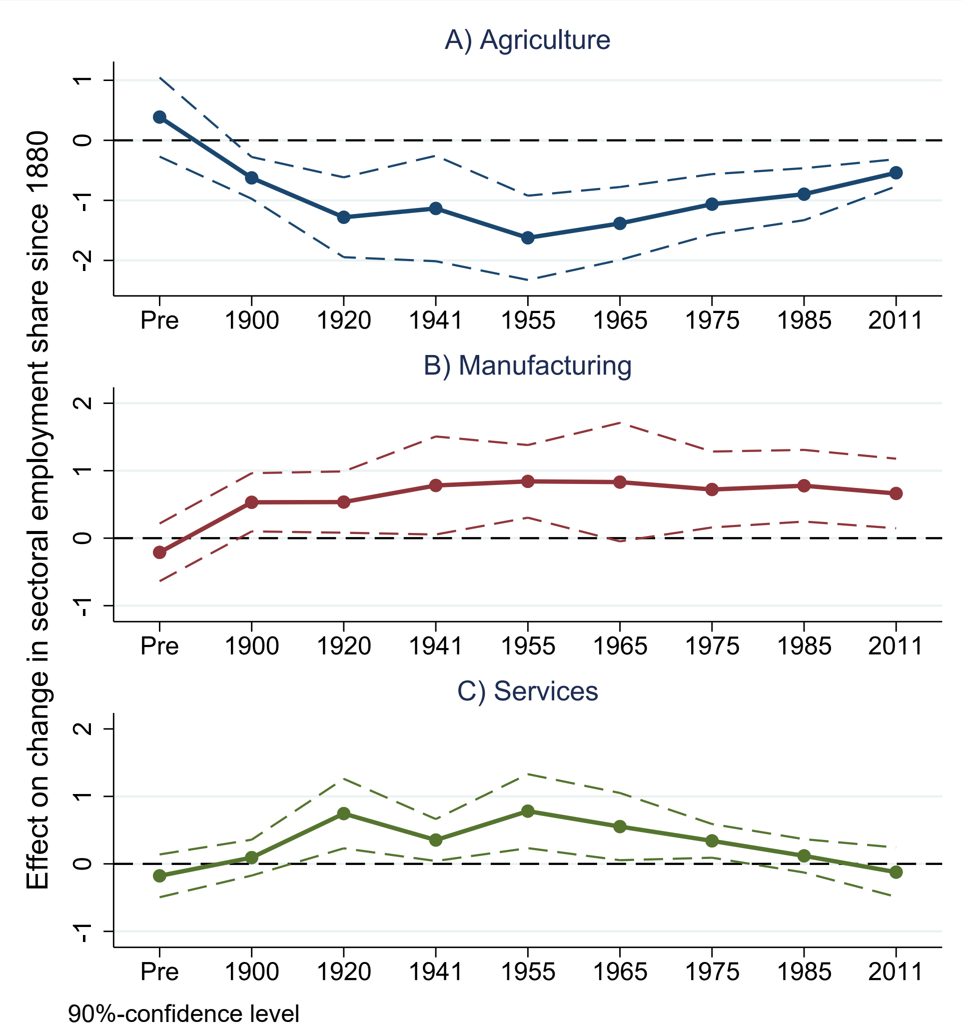
4.2 Long-run effect from the early adoption of electricity

I now turn to my second key question: whether the effect of early adoption of electricity had a long-run effect on economic development. Figure 7 presents the IV estimates, based on Equation 4, for the effect of early electricity adoption on structural change in the long-run showing. The results highlight that the effect of early electricity adoption on economic development persists up to today.[51] The first-panel presents the coefficient for the effect of the change in electricity 1880-1900 on the agricultural employment share over time. The first two coefficients present the previously presented results for the periods 1860-1880 (pre-period) and 1880-1900 (contemporaneous-period) for comparison. The next coefficients presents the effect for the periods after 1900 with the size of the coefficient continuing to increase in magnitude till 1955. In 1955 the effect of the early adoption of electricity on the agricultural employment share is greatest with the coefficient of -1.624 suggesting a 8.1 percentage points smaller agricultural employment share in a district that experienced a one standard deviation higher electricity adoption 1880-1900. After 1955 the magnitude of the effect declines over time. 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 early electricity adoption.

The second panel of Figure 7 shows the effect of early electricity adoption on the manufacturing employment share. The coefficients suggest that early electricity adoption strongly contributed to increasing industrialization till the mid-20th century with the

[51] Appendix Figure A.5 present the corresponding OLS estimates. These despite being downward biased suggest also a considerable persist effect on structural transformation.

Figure 7: 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 (1900, 1920, 1941, 1955, 1965, 2011) as well as the pre-trend period 1860-1880. Log waterpower potential per person is used as the instrument. Regressions include the full set of baseline controls and robust standard errors are clustered at the cantonal level. The pre-trend period includes initial controls for the year 1860. The regression for the period 1880-1920 includes a control for the change in electricity produced per person between 1900-20. For the periods 1941, 1955, 1965, 1975, 1985, 2011 the change in the number of waterpower plants is included as an additional control. Each presented coefficient based on an individual regression with 178 observations (Pre-period N=177). Appendix Table B.4 presents the estimated coefficients for electricity adoption 1880-1900 and 1900-t for 1920-2011.

effect after this remaining relatively 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.[52] This illustrates that the increase in

[52]This might appear surprising considering recent de-industrialization in most advanced economies. However, manufacturing still continues to represent a sizeable share of employment in Switzerland today (see Appendix Figure C.5). Further, productivity differences in manufacturing at least across countries appear remarkably stable over time compared to other sectors and economic convergence between

electricity production between 1880-1900 triggered a process of industrialization in districts earlier exposed to electricity 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 7 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 does not seem to be as persistent over time as the effect on the agricultural and manufacturing employment shares.

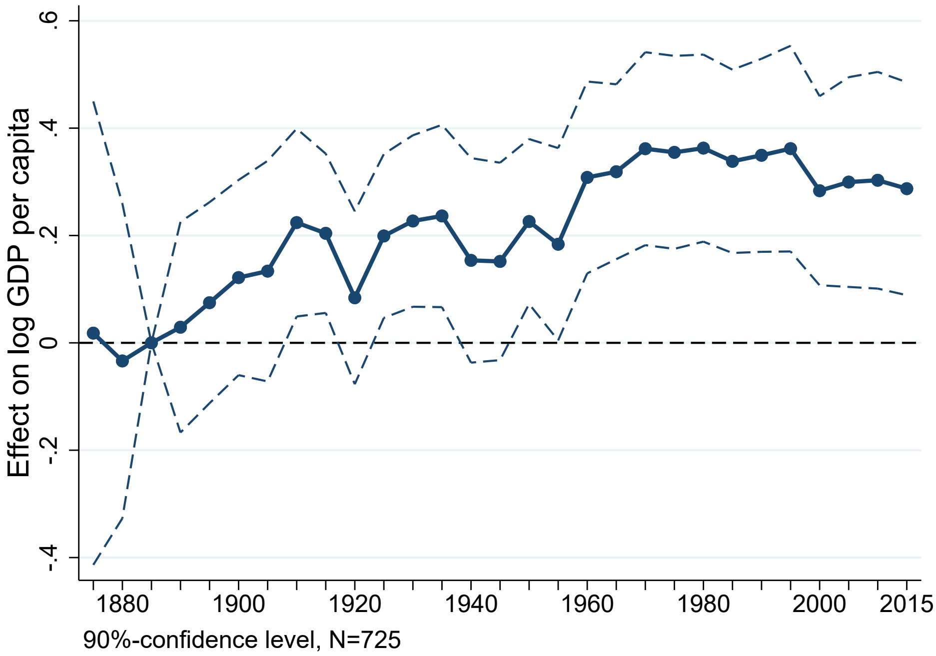
In general, this pattern is also observed when looking at overall employment across sectors. Areas exposed earlier to electricity continued to experience significantly higher employment growth (decline) in manufacturing (agriculture) throughout the 20th century, and not just a change to the level of industrialization (see Appendix Table B.5) with employment growth rates converging 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 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.[53]

The different ways of measuring here reflect two distinct interpretations of the effect of early electricity adoption on economic development across districts. First, the measure using employment shares reflects differences in economic development across districts for the average person (corresponding to GDP per capita). Second, the measure using employment numbers reflects differences across districts in overall economic activity (corresponding to comparing overall GDP). The difference in estimates suggests that migration and commuting attenuated per capita differences across districts in Switzerland that occurred due to the earlier adoption of electricity in the long-run. Consequently, differences in economic activity per person appear less pronounced than in overall economic activity. Despite this, both the geographic distribution of economic activity as well as the per capita level of economic development continue to be affected by the early adoption of electricity more than 100 years later.

countries mainly occurred through shifting labour out of agriculture into services (see e.g. Bernard & Jones 1996; Broadberry 1998). This might help explain why differences across districts persisted even as overall manufacturing employment started to decline, while there appears to be convergence in services employment despite it growing in importance overall.

[53]Note also that the effect on the local service employment share peaks just as the construction of the Swiss motorway system starts. One interpretation of this is that this allowed services to be easier provided across districts suggesting potential positive economic spillovers from the early adoption of electricity on neighbouring areas, while at the same time attenuating the local estimate.

Figure 8: 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 sizeable 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 long-run differences in economic activity 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 8 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. However, the divergence in incomes continued after these disruptions. Only from the 1970s onwards the income differences stabilized at a relatively constant level that persists up to today.

Further evidence that the early adoption of electricity had a long-run effect on economic development can also be seen in Table 5, which presents the effect of the early adoption of electricity on the current level of economic development measured by education and income. First, Panel A column 1 presents the effect on median income in

Table 5: Effect of early electricity adoption on current outcomes

	Income		*Education*	
	Average	*Median*	*Secondary*	*Tertiary*
A. Districts	(1)	(2)	(3)	(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
B. Cantons				
Δ Electricity pp 1880-1900	233.3	224.1**	1.326+	0.863*
	(183.1)	(95.24)	(0.981)	(0.482)
Region FE	No	No	No	No
Other controls	Yes	Yes	Yes	Yes
N	25	25	25	25

Notes: The regressions present the IV results for the effect of electricity adoption between 1880-1900 on the 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, respectively. Panel A presents the effect across districts and Panel B presents the corresponding results across Cantons. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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. A crucial determinant of higher earnings between individuals is usually the level of education Mincer (1974). In addition, secondary and tertiary education are also 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).[54] 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 2.02 percentage points higher and the share of tertiary education is 0.98 percentage points higher. Panel B presents the corresponding estimates at the Cantonal level. The estimated effects are considerably larger in magnitude. This again suggests that the observed local effect might be attenuated by spillovers through commuting and migration in the long-run, which plays less of a role the larger the geographic area of analysis.

Two features are crucial to be able to conclude that the effect is only from exposure in the initial 20 years of electricity adoption. First, the extension of the electricity grid across

[54]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.

Switzerland rapidly equalised 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). So while there was some initial difference in access to electricity across Switzerland, access to electricity rapidly became universal after 1900. Universal access might however still not be sufficient to support that the 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.[55] 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 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 insignificant.[56] This is further confirmed by Panel B showing that there is no considerable difference in electricity usage across all manufacturing and services firms also by 1955. These results suggest that the extension of the electricity grid in the early 20th century lead to a convergence in electricity usage between districts by at least the 1930s.

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 that might be correlated with the initial adoption. This post-1900 increase in electricity generation also had a positive effect on industrialization itself (see Appendix Table B.4).[57]

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 indus-

[55] 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 countries.

[56] 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 (see Figure 2). 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).

[57] Appendix Table B.4 highlights that electricity generation after 1900 had an effect on economic development as well and if not controlled for the effect of early electricity adoption on structural change would have falsely been estimated to be about 10%-20% larger across most results (see Appendix Figure A.6). However, in line with the rapid extension of the electricity grid across Switzerland, the effect of waterpower plants build for electricity generation after 1900 only increased employment in electricity generation itself (see Appendix Table B.7) and had no positive effect on other industries.

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
N	178	178	178

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 (Panel A), while for 1955 it covers all manufacturing and services (Panel B). In 1929, 5 districts report zero factories which are treated as missing values. The 1929 data only reports total energy used at the district level and measures were adjusted based on the usage of electricity versus other sources at the cantonal level. Notably, already 87.4% of the energy used in Swiss factories was reported as being electric in 1929 (451640kW electric of 516457kW in total). Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

try here is based foremost on occupation rather than firm.[58] This provides two insights: First it allows to distinguish whether the adoption of electricity affected mainly industries 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. However, the latter were relatively easy to transport and did not necessarily need to be constructed locally.[59] On the other hand, these industries might also have been affected through using electricity. The remaining four industry groups use electricity, but are not

[58]The enumeration in the historic Swiss censuses to industries is based foremost on main profession and the type of product produced by an individual rather than the industry of the firm. 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. Bundesamt für Statistik 1920, Volume 3, p.31-34 provides a cross-tabulation of the employment in industries based on occupation versus firm for 1910. In general there is considerable overlap, but for example for "Electricity generation" the employment by occupation (5321) is about twice as high as by firm (2649) suggesting considerable employment of workers focussing on electricity generation within firms that specialise on producing different goods.

[59]That water-turbines were built somewhere else and transported to the site of usage is also underlined by the machinery industry having mostly developed beforehand in close proximity to the existing

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.

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. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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.[60] 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 that there is no local effect on employment in "Machinery, watches, & other metal". This is unsurprising as turbines were usually constructed somewhere else and transported to waterpower plants rather than produced locally. These three effects combined can be

textile industry and that water-turbines accounted for 9% of Swiss exports in 1900 (see "Turbinen" and "Maschinenindustrie" in HLS 2020).

[60]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.

seen as the upper-bound of the direct effect of electricity generation on manufacturing employment. Together Column 1-3 explain most 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 appears to not just have contributed to the emergence of new industries, but also made existing ones more competitive. This is suggested by column 5 as employment in "Textiles & apparel" was positively affected from 1920 onwards.[61] The use of electricity in the textile industry appears to have been especially beneficial for small scale producers and provided new prospects for the mechanization of certain production processes (Stiel 1933). 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. 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 and declines to 18% in 1920 and 4% in 1975). By 1975, the remaining employment in the Swiss textile industry was in innovative firms, which produced specialised products (industrial textiles for cars and planes, medical textiles, heat and other resistant textiles etc.) and no longer bulk goods (see "Textilindustrie" in HLS 2020). Column 6 highlights that in line with the decline in agricultural employment also employment in "Food products" (predominantly the making of cheese and meat products) declined. However, employment recovered afterwards to some extent. This likely reflects that some workers moved from agriculture and food processing into construction, but returned afterwards. Column 7 highlights there is little effect on other industries.

The presented results suggest that the long-run effect of the early adoption of electricity on manufacturing employment was mainly from its use rather than its generation. By 1975, the employment growth in manufacturing observed is mostly due to a persistent

[61] Appendix Table B.6 highlights that this is also reflected in female employment growth between 1900-1920 that made up most of the workforce in "Textiles & apparel". In contrast, male employment growth stagnated after 1900. This suggests that workers in "Construction, wood & stone products", predominately male, likely returned to their previous occupations in agriculture and food processing after 1900, rather than obtained employment in textile industries with the employment growth here likely being due to women newly entering the labour market.

effect of the early adoption of electricity on employment in “Chemicals” and “Textiles & apparel”, and to a smaller extent in “Electricity generation” (the employment effect is less than a tenth in the other two). In all other industries lower employment is observed (with a significant decline for “Machinery, watches, & other metal”). This decline likely reflects increasing industrial specialization in the second half of the 20th century as most surplus labour had already left agriculture (see Appendix Figure C.5). Accordingly, the overall manufacturing employment share could no longer easily expand, but rather an internal reallocation in employment had to occur from the least competitive to most competitive manufacturing industries.[62]

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 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 by 1900 (1975).[63] 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.

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

[62]Notably, the persistent higher employment share in “Textiles & apparel” might also be interpreted as a technological lock-in of districts in less modern industries (compared to “Machinery, watches, & other metal”) for a part of industrial employment. However as shown, the overall impact of the early adoption of electricity was clearly positive, which does not support that higher employment in these industries leads to districts earlier exposed to electricity having a lower overall productivity.

[63]Appendix Figure A.7 presents the corresponding employment shares for industries in 1860, 1900 and 1975. That the adoption of electricity explains only 27.1% of employment in electricity by 1900 likely reflects that employment is related to the number of waterpower plants rather than the electricity generated as larger ones generated a multiple of the energy of small ones while employment was rather similar. This is also why number of waterpower plants build is used as control after 1920, when electricity generation and use were definitely no longer correlated.

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 that seems implausible is that differences in the use of electricity persisted even after the electricity grid extended across the whole of Switzerland. However, results in Table 6 show that, by 1929, early adoption of electricity had no significant effect on electricity use.

The third potential mechanism often able to explain persistence of differences in economic development even after initial advantages disappear is population or industry agglomeration due to sizeable economies of scale (see e.g. Krugman 1991; Bleakley & Lin 2012). However, again some of the already presented results appear to provide little support for this mechanism. First, there is no evidence of population growth as there is no increase in migration into areas that adopted electricity early (see Table 3). Instead local employment growth appears driven by successive increases in male and female labour force participation (see Appendix Table B.6). Further, even the observed employment growth starts to slow after 1900, rather than accelerate over-time as in Bleakley & Lin (2012). Second, while the presented growth pattern of the newly developing chemical industries (see 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. 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, I suggest that human capital accumulation and innovation are more plausible explanations for the long run effect of the early adoption of electricity. Recent contributions in growth theory suggest that technical change can increase human capital formation (see e.g. Galor & Moav 2006; Galor 2011),[64] which in turn is a main driver of economic growth (see e.g. Romer 1990; Goldin & Katz 2001). Notably, Table 5 already suggested higher levels of education today in districts that adopted electricity earlier. However, for this to be a crucial mechanism,

[64] 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.

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. 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 organised since 1874, covering the whole male Swiss population so that military test scores reflect the education level at age 19 across different districts. Importantly, the test scores at the district level are based on the location of the primary school a recruit had visited as it was common at the time in Switzerland to migrate for secondary schooling. Here, the top-mark received closely relates to educational attainments at the secondary level of schooling rather than primary schooling, while the worst two marks correspond to insufficient knowledge even at the level of primary schooling.[65] 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, e.g.: "Someone 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?"

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 covering 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.

Panel B looks at the period 1880-1910 reflecting the effect on educational outcomes a decade later. Column 1 shows that the effect nearly doubled with a standard deviation

[65] Only 8 out of 100 tested that only attended primary schooling received the top mark, while 65 out of 100 did so that attended secondary schooling. 20 out of 100 tested, which only visited a primary school, received a 4 or 5 constituting a failure to complete rudimentary tasks in the subject area, while non that attended secondary education did.

Table 8: Effect of electricity on human capital accumulation

A. Secondary education 1880-1900	Overall (1)	Reading (2)	Writing (3)	Math (4)	General (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 share of passing marks (corresponding to basic primary education) across different subjects 1880 to 1900 and 1910. Marks are given between 1 and 5, with 1 being the best mark and 5 the worst (both 4 and 5 constitute a fail). Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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. The result suggests the greatest improvement in educational outcomes occurred in the more complex subjects, which at the time represented upper-tail human capital.[66] 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.[67] 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.[68] Table 9 looks at the effect of the early adoption of electricity on students in dual education in 1910 (Panel A) and

[66] 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).

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

[68] The long-term income gains from vocational training in developed countries today have been highlighted for example by Neuman & Ziderman (1991). This type of education also provides exactly the

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). Nearly no improvement in the dual education system is observable across these specification. However, this might not be so surprising as districts with a small population usually had no dual-education institution of their own as they would be underutilized, so instead it was common for students to temporarily migrate for the purpose of schooling.[69] 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 number of departments is observed, suggesting a reorganization rather than an extension of education.[70]

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' historic support for the provision of government funded education. Table 10 Panel A presents the effect of early electricity adoption on support in referendums focussed 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. 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 more highly, which in turn likely led to higher individual and municipal investments into education. Indeed, national influence on education policy was low far into the 20th century so that

kind specific training a labour force requires to utilize new technologies and therefore is critical in the diffusion of technology (Rosenberg 1972).

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

[70] 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.

local policy decisions where likely much more crucial for the provision of education. Some evidence for this is observable in increased municipal and cantonal spending, in particular for secondary education, across cantons (see Appendix Table B.8).

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 centres only. Vocational schools comprise professional ("Berufsschulen"), craft ("Handwerksschulen"), and commercial schools ("Handelsschulen"). The category of polytechnic universities (by department if reported) also includes all design schools ("Zeichnungsschulen" training architects, designers, etc.) which in some cases, but not always are parts of polytechnic universities. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 10: Effect of electricity on education and infrastructure demand

	1902	1963	1964	1973	1973	1978
A. Support education	(1)	(2)	(3)	(4)	(5)	(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)
	1877	1891	1897	1927	1945	1987
B. Support infrastructure	(7)	(8)	(9)	(10)	(11)	(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 Appendix Table C.2. 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

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 2000 population as city if more than 25000, town 10000-25000 inhabitants and rural less than 10000 inhabitants. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

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.[71] 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 centres that usually are the main drivers of innovation to rather less densely populated areas. While it is impossible to evaluate the level of innovation in these areas in 1880 as no patent law existed in Switzerland at that time, it appears clear that these areas were not technologically leading at the international level at the end of the 19th century. This suggests that adoption of electricity allowed these areas to leapfrog to the forefront of innovation (see e.g. Brezis & Krugman 1997).

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.

[71] A one standard deviation higher exposure to early electricity adoption leads to 6 more patents per 1000 inhabitants since 1980 with the corresponding average number of patents being 21 per 1000 inhabitants suggesting that innovation increased by 28%.

However, the rather random nature of the early adoption of electricity across Switzerland, which was related to randomly located 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 (see e.g. 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.[72] 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 kilometre 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 expansive the construction of infrastructure was in those areas as tunnels are the main cost factor per kilometre of railroad lines in Switzerland. 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.

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 increased immediately after this advantages started to disappear 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 centre of Europe might have been of crucial importance in allowing 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

[72] This also seems of particular interest as for developing countries today it appears that big infrastructure investments only have a positive effect on industrialization when these are combined with access to electricity (see Moneke 2019).

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 between 1880-1900 persistently increased industrialization and incomes across Switzerland, even though differences in its use quickly disappeared due to the rapid extensions of the electricity grid after 1900. 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 no 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 leat initially no in-migration appears to have occurred suggesting 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 electricity adoption could be driven by economic considerations at the time. These initial geographic constraints on the adoption of electricity led to its early adoption not just in urban centres, 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 not just in urban centres, but also in rural areas. It also underlines that certain geographical features can have a lasting effect on economic development despite being relevant only for a 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 and negative effects far beyond disruptions caused in the labour market during their implementation.

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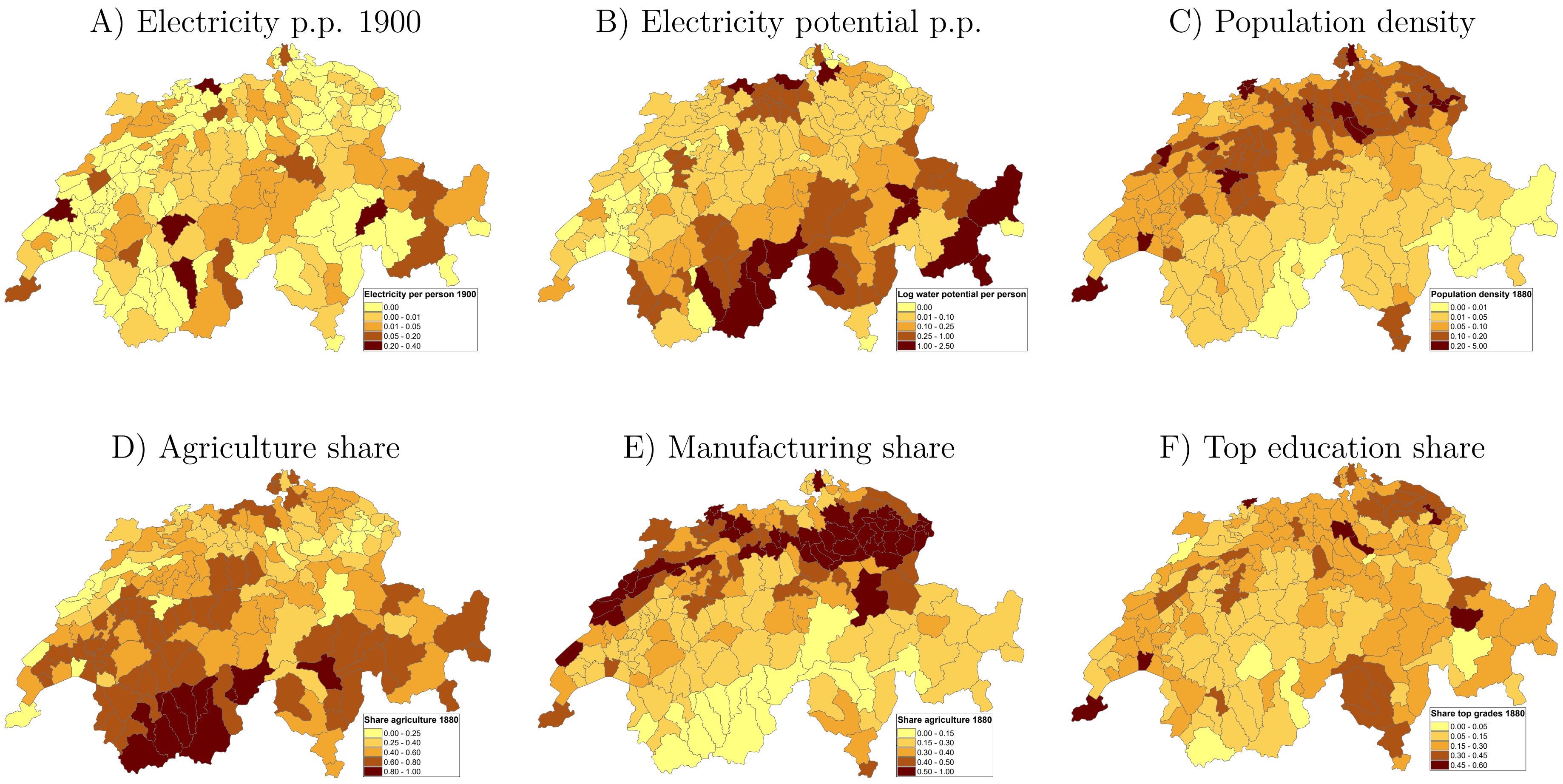
Appendix

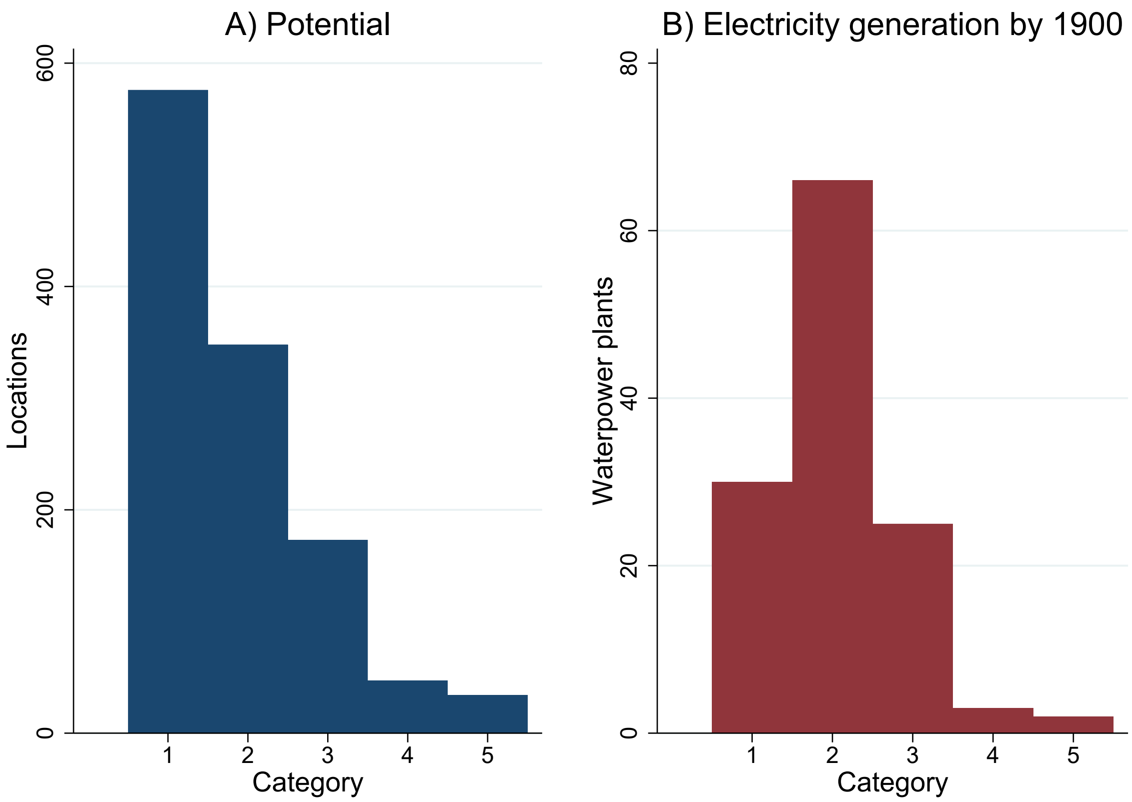
A Figures

Figure A.1: Descriptive maps for Switzerland



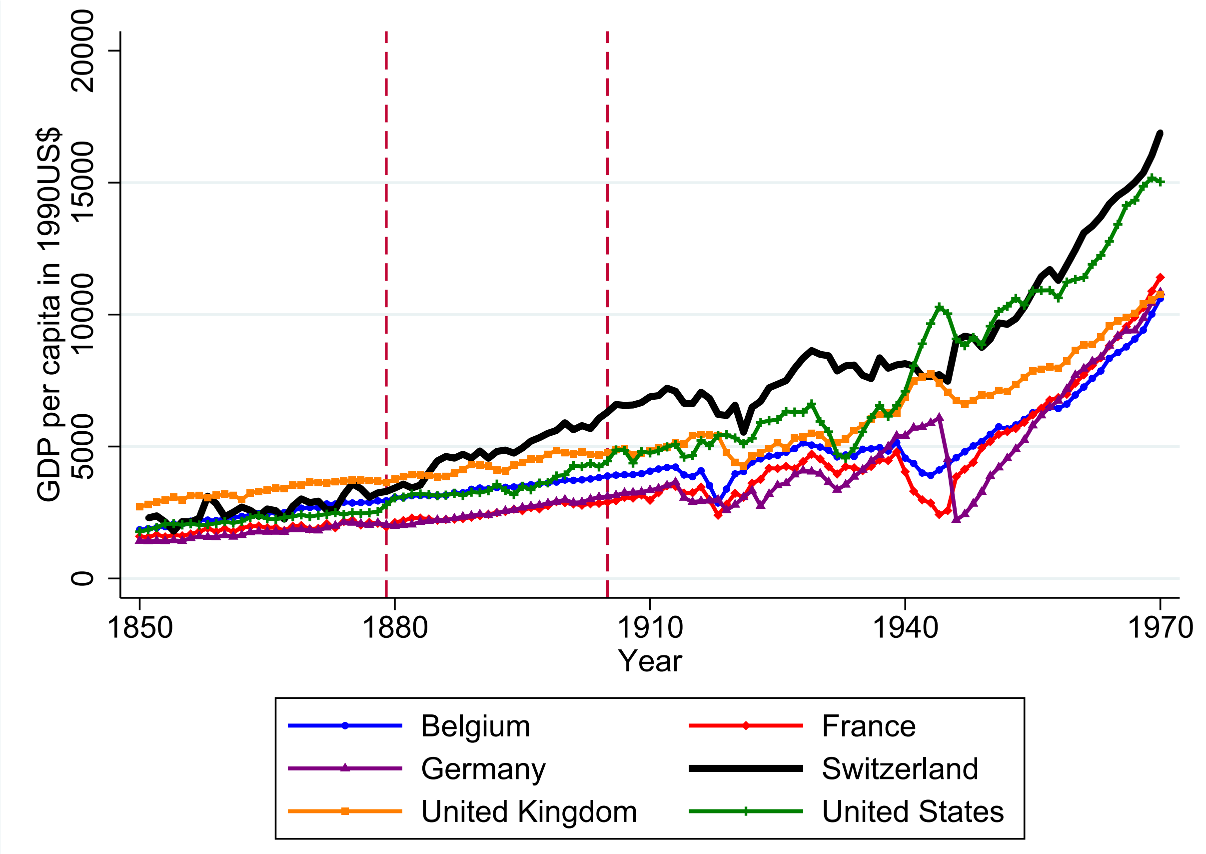
Notes: The figures depict A) kW of electricity per person in 1900, B) log water power potential, C) populations density in 1880, D) agricultural employment share in 1880, E) manufacturing employment share in 1880, and F) share of top marks in military education tests in 1880. More detail available when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

Figure A.2: Size of potential and actual electric power plants



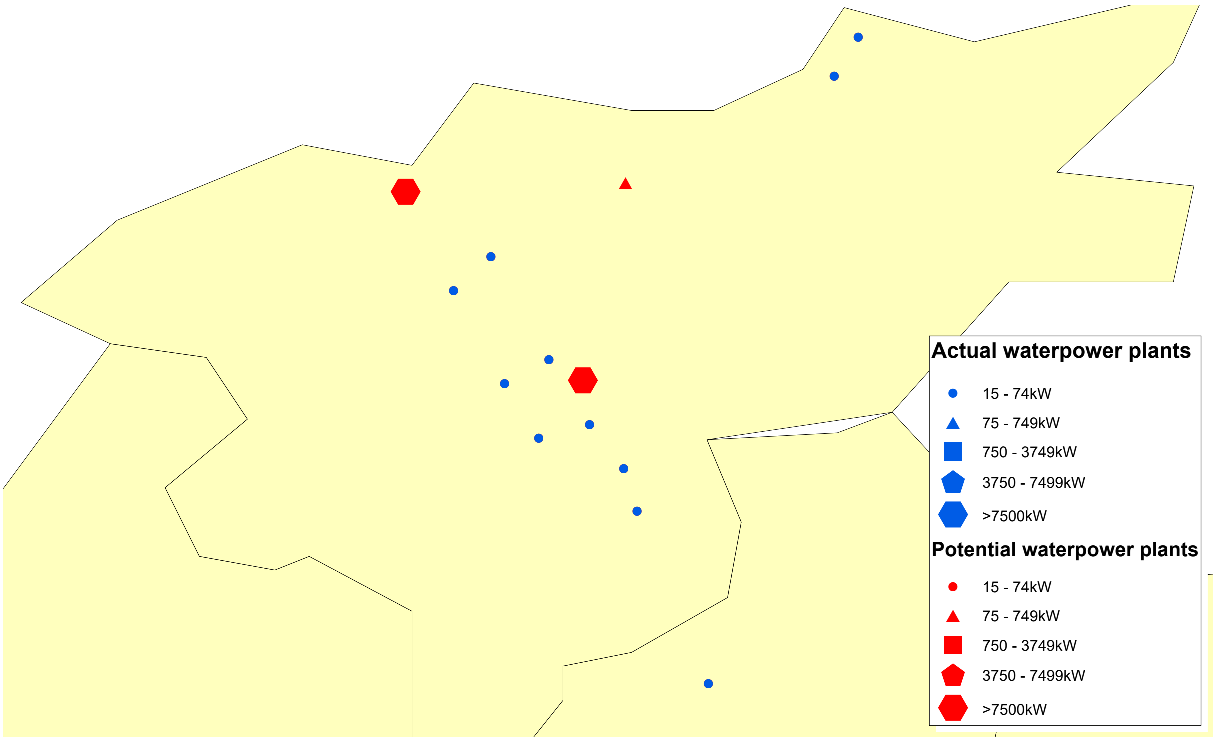
Notes: The histogram shows the number of potential and build water-power plants generating electricity in 1900 by size in Switzerland as reported in Bossard (1916). The 5 categories are: (1) 20-99HP, (2) 100-999HP, (3) 1000-4999HP, (4) 5000-9999HP and (5) above 10000HP with 1HP being equal to 0.75kW. The category of the build water-power plants in 1900 is based on actual energy produced, the potential of the location the power-plant is build on can be in a higher category. Locations requiring an embankment dam are not recorded (none of these were build by 1900).

Figure A.3: Economic output across countries 1850-1970



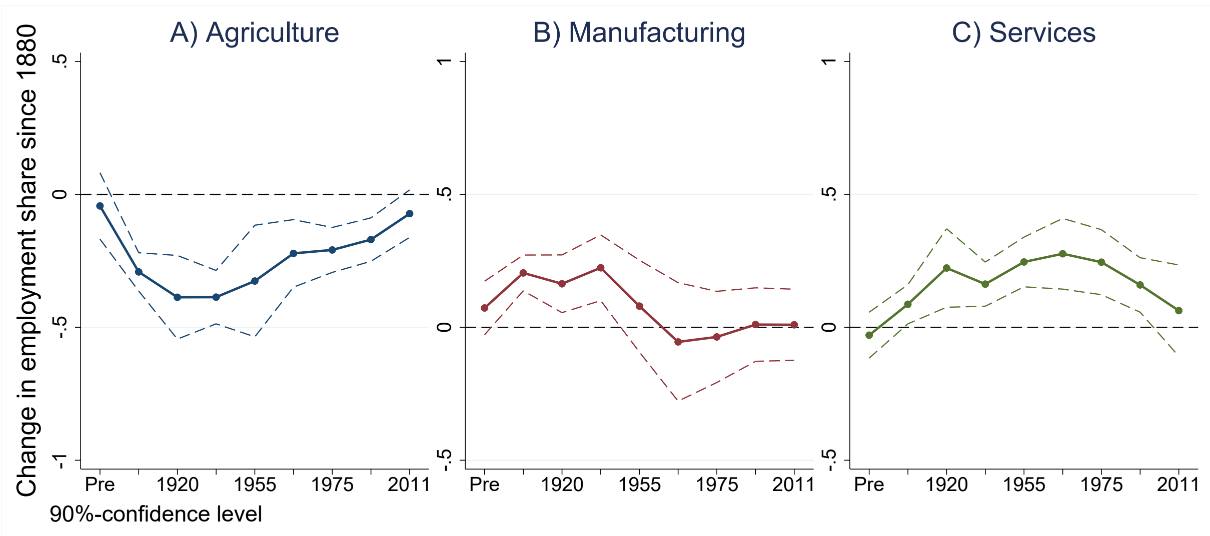
Notes: Real GDP per capita in 1990US$ across leading industrial countries from 1850-1970. The first line in 1879 reflects the initial commercial usage of electricity in Switzerland, the adoption of electrical lights at the Kulm Hotel in St. Moritz powered by a 7kW plant. The second line represents 1905 when Switzerland had the highest per capita production of electricity in the world with this leadership in adoption quickly diminishing in the following years (see "Elektrifizierung" in HLS 2020). Source: Bolt et al. (2018)

Figure A.4: Existing and potential waterpower plants in Basel-City 1900



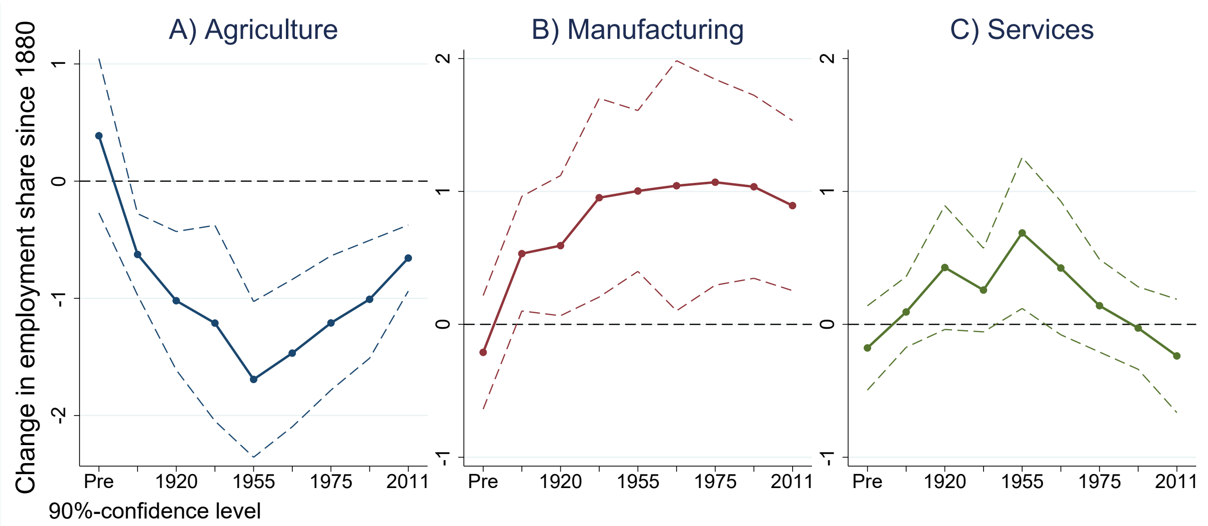
Notes: The map shows the existing (blue) and potential (red) waterpower plants in the Canton of Basel-City by 1900. The former are mostly watermills dating back to the middle ages. Source: Bossard 1916

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



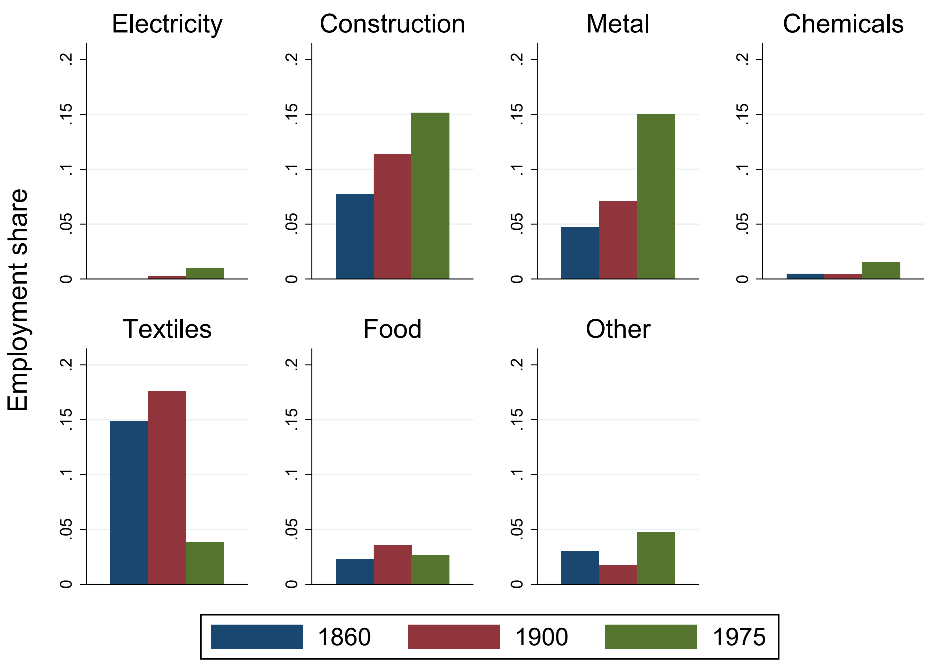
Notes: This figure presents the corresponding OLS estimates to Figure 7.

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



Notes: This figure presents the corresponding estimates to Figure 7 without controlling for the adoption of electricity after 1900.

Figure A.7: Employment shares across industries 1860-1975



Notes: The figure presents employment shares of industry groups in total employment in 1860, 1900 and 1975. Employment shares represent the average across 178 districts in the sample.

B Tables

Table B.1: Balance checks actual and potential electricity adoption

	Control		Treatment			
Variable	Mean	N	Mean	N	Diff	P value
A1. Difference between no-electricity vs. electricty 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	
Share secondary education (1880)	0.22	93	0.21	85	0.005	
Altitude (km)	0.90	93	1.02	85	-0.115	
Longitude	8.01	93	8.16	85	-0.143	
Latitude	47.00	93	46.96	85	0.034	
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	
Share secondary education (1880)	0.22	93	0.22	60	-0.001	
Altitude (km)	0.90	93	1.05	60	-0.150	
Longitude	8.01	93	8.15	60	-0.134	
Latitude	47.00	93	46.96	60	0.034	
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	
Share secondary education (1880)	0.24	29	0.21	149	0.033	
Altitude (km)	0.75	29	1.00	149	-0.246	**
Longitude	7.55	29	8.19	149	-0.633	* * *
Latitude	46.93	29	46.99	149	-0.064	
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	
Share secondary education (1880)	0.24	29	0.21	60	0.033	
Altitude (km)	0.75	29	1.29	60	-0.533	* * *
Longitude	7.55	29	8.21	60	-0.658	* * *
Latitude	46.93	29	46.78	60	0.145	

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

Table B.2: Additional robustness checks for the effect of electricity adoption on the 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: For all regressions the dependent variable is the change in the share of employment in agriculture between 1880 and 1900. Further controls included corresponds to the ones used in column 5 of Table 2. 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 B.3: Evaluating alternative instrument: Modern potential

A. Alternative IV	(1)	(2)	(3)	(4)	(5)
Δ Electricity pp 1880-1900	-0.428	-1.528*	-1.403*	-1.311*	-1.476*
	(0.440)	(0.794)	(0.752)	(0.733)	(0.888)
F-stat (1st stage)	12.37	6.01	5.96	5.69	3.79
B. Alternative Reduced Form					
Log waterpower potential pp (modern)	-0.003	-0.019***	-0.018***	-0.016**	-0.018***
	(0.003)	(0.005)	(0.006)	(0.006)	(0.005)
C. Alternative First Stage					
Log waterpower potential pp (modern)	0.008***	0.012**	0.013**	0.012**	0.012*
	(0.002)	(0.005)	(0.005)	(0.005)	(0.006)
D. Comparison instruments					
Log waterpower potential pp	0.048***	0.049***	0.051***	0.052***	0.055***
	(0.015)	(0.017)	(0.018)	(0.018)	(0.020)
Log waterpower potential pp (modern)	-0.000	0.001	0.002	0.001	0.002
	(0.004)	(0.009)	(0.009)	(0.009)	(0.010)
Controls	See controls included in Table 2				
N	178	178	178	178	178

Notes: The table illustrates an alternative instrument based on the potential of small hydropower plants in Switzerland (see Schröder et al. 2012). The data depicts the estimated electricity production potential of all natural flowing bodies of water in Switzerland (excluding main rivers as the Rhine, Rhone and Aare which are to large for small hydropower plants). Further, modern day structures of water-management alter the recorded potential. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.4: Estimates for effect of electricity adoption on structural change

A. 1880-1920	Agriculture (1)	Manufacturing (2)	Services (3)
Δ Electricity pp 1880-1900	-1.281***	0.535*	0.746**
	(0.404)	(0.276)	(0.313)
Δ Electricity pp 1900-1920	0.028**	0.006	-0.034**
	(0.013)	(0.016)	(0.017)
B. 1880-1941			
Δ Electricity pp 1880-1900	-1.135**	0.781*	0.354*
	(0.534)	(0.442)	(0.189)
Change waterpowerplants 1900-1941	-0.005	0.011**	-0.006
	(0.004)	(0.005)	(0.005)
C. 1880-1955			
Δ Electricity pp 1880-1900	-1.624***	0.842**	0.782**
	(0.427)	(0.327)	(0.333)
Change waterpowerplants 1900-1955	-0.004	0.010**	-0.006+
	(0.004)	(0.005)	(0.004)
D. 1880-1965			
Δ Electricity pp 1880-1900	-1.384***	0.831+	0.553*
	(0.369)	(0.534)	(0.303)
Change waterpowerplants 1900-1965	-0.003	0.009*	-0.005+
	(0.003)	(0.004)	(0.003)
E. 1880-1975			
Δ Electricity pp 1880-1900	-1.063***	0.722**	0.341**
	(0.304)	(0.342)	(0.152)
Change waterpowerplants 1900-1975	-0.005**	0.011**	-0.006+
	(0.002)	(0.005)	(0.004)
F. 1880-1985			
Δ Electricity pp 1880-1900	-0.897***	0.777**	0.119
	(0.263)	(0.323)	(0.150)
Change waterpowerplants 1900-1985	-0.004*	0.008**	-0.005+
	(0.002)	(0.004)	(0.003)
G. 1880-2011			
Δ Electricity pp 1880-1900	-0.540***	0.663**	-0.122
	(0.137)	(0.314)	(0.222)
Change waterpowerplants 1900-2011	-0.003**	0.005+	-0.003
	(0.001)	(0.004)	(0.003)
Controls	Yes	Yes	Yes
N	178	178	178

Notes: The regressions present the results on the long-run effect. The dependent variables are the change in the share of employment in agriculture, manufacturing and services for the specified time-periods. All specification represent the IV-results using the potential waterpower per person as instrument for the change in electricity produced between 1880 and 1900. All specifications in addition to initial controls also include the change in the number of water-power plants per person between 1900 and the respective end date. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.5: 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 regressions present the results for the effect of initial 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 B.6: 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 regressions present the results for the effect of electricity on the growth rate of employment for the periods 1880-1900, 1900-1920 and 1920-1941. Panel A presents the results on total employment growth in a district. Panel B and C present the corresponding effect for male and female employment growth, respectively. Robust standard errors in parentheses are clustered at the cantonal level. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table B.7: 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	124	124	124	124	124	124	124

Notes: The regressions present the OLS results for the effect of the increase in electricity generation 1900-1920 on the change in the share of employment across manufacturing industries between 1900 and 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 B.8: Effect of electricity on education spending

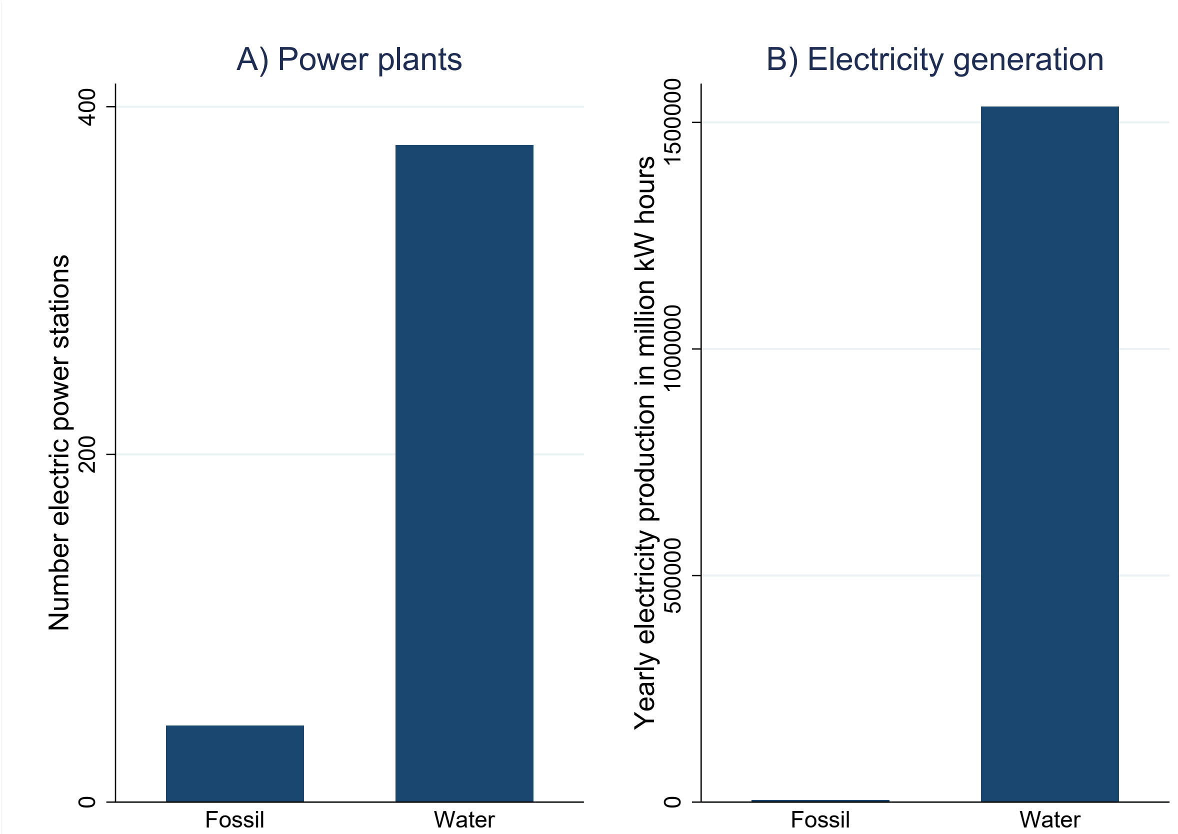
	Primary (1)	Secondary (2)
Δ Electricity per person 1880-1900	0.730*	9.846**
	(0.406)	(4.951)
Controls	Yes	Yes
N	25	24

Notes: The regressions present the results for the effect of electricity from waterpower on the change in the municipal and cantonal spending at the primary and secondary level. Data was only available at the cantonal level and from 1887 onwards. Robust standard errors in parentheses. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

C Data Appendix

C.1 Electricity data

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



Notes: Type of primary power-plants by number and actual kW hours of electricity produced over a year in 1916. To the best of my knowledge 1916 is the earliest comprehensive survey of fossil fuel power plants available. Note, that of the reported fossil fuel power plants many appear to have been operated adjacent to waterpower plants. Source: Department des Inneren 1891-1920.

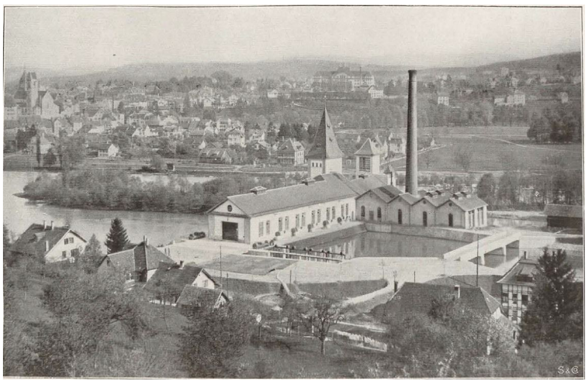
My data on electricity production by waterpower plants and waterpower potential is collected from "The waterpower of Switzerland in 1914" (Bossard 1916) compiled by the water-management agency ("Abteilung für Wasserwirtschaft") of the Swiss department of the interior ("Department des Innern").[73] The electricity produced from waterpower represented the vast majority of electricity production in the early stages of electrification in Switzerland (see Figure C.1). The low importance of fossil fuels for electricity production was due to Switzerland being scarce in natural resources and requiring expensive coal imports making the generation of electricity from coal uneconomical (Bossard 1916).

[73] 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.

Even the remaining negligible generation of electricity from coal appears to have been mostly located at hydroelectric power-plants to compensate for variations in the water level (Roth 1920). 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).[74] In the cases waterpower plants lay within different administrative boundaries, the respective allocation of energy generated is reported for each administrative unit separately in Bossard (1916). Accordingly, between 1880 and 1900 the production and supply of electricity were extremely localised so that electricity needed to be produced in the district it was consumed.

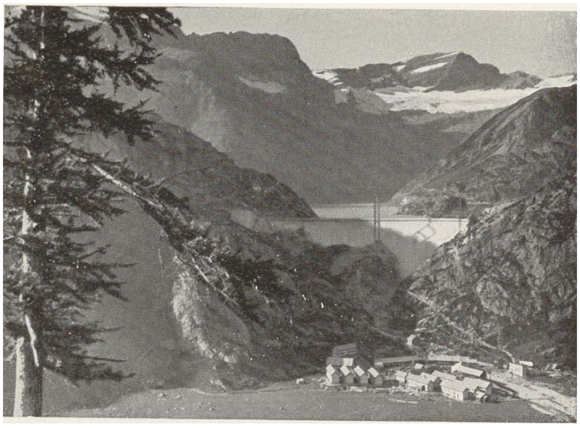
Figure C.2: Examples of waterpower plants

A) without embankment dam



Waterpower plant build in Aarau in 1894 owned by the municipality of Aarau with an electricity production of 705kW.

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.

First, "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). I use the average power generated as the measure of energy supplied by a power-plant and allocate this energy to two groups: (i)

[74]Note that 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 in 1901 on average only supplied electricity to 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 pattern is in-line with the drastic shift in the production of electricity from small private suppliers of electricity to cantonal electricity companies at the start of the 1900s as described in HLS (2020) "Elektrizitätswirtschaft".

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 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 of 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).

Second, for the instrument I digitize information presented in a map in "The waterpower of Switzerland in 1914" about the precise location of existing and potential waterpower plants and their specific features presented through illustrations of the existing and planned canals, pressure pipes towards and out of the turbine house, and whether a 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 plants 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. 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.

The mapped waterpower plants can be distuinguished into two specific groups those not requiring an embankment and those requiring an embankment. Historic examples of the two types of waterpower plants are provided in Figure C.2. The first waterpower plant requiring an embankment dam was only build in 1908 and only two existed by 1914. Due to waterpower plants with embankment dams not being related to any actually build waterpower plants by 1900, including these would provide a less relevant first stage.[75] Waterpower plants without and with an embankment dam are also distinctly marked 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 districts total potential.

Table C.1 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 when potential waterpower plants with embankment dams do not provide a relevant first-stage for the adoption of electricity by 1900. However as Panel B shows, potential waterpower plants with embankment dams become relevant after 1900 for the location of modern waterpower plants.

Figure C.3 presents the map of all digitized existing (in 1914) and potential powerplants with their location in Switzerland. An excerpt of the corresponding original map

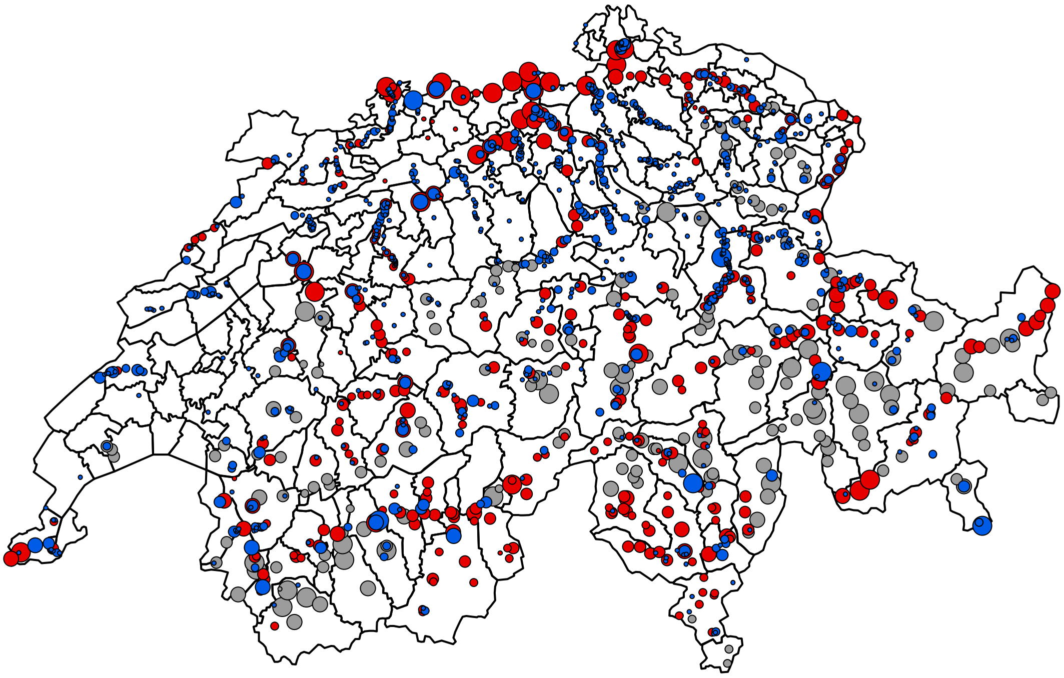
[75] In addition, one might be more concerned that the decision on where to locate an artificial lake for the embankment dam might influenced by considerations other than maximising electricity output. However, the map does illustrate several embankment dams that would have required the flooding of multiple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

Table C.1: 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. Note, column 1 is the first-stage of the baseline specification Table 2 Column 5. Column 3 and 4 estimate the same relationship for 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. $^{+}$ $p < 0.20$, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Figure C.3: Location of existing and potential waterpower plants 1914



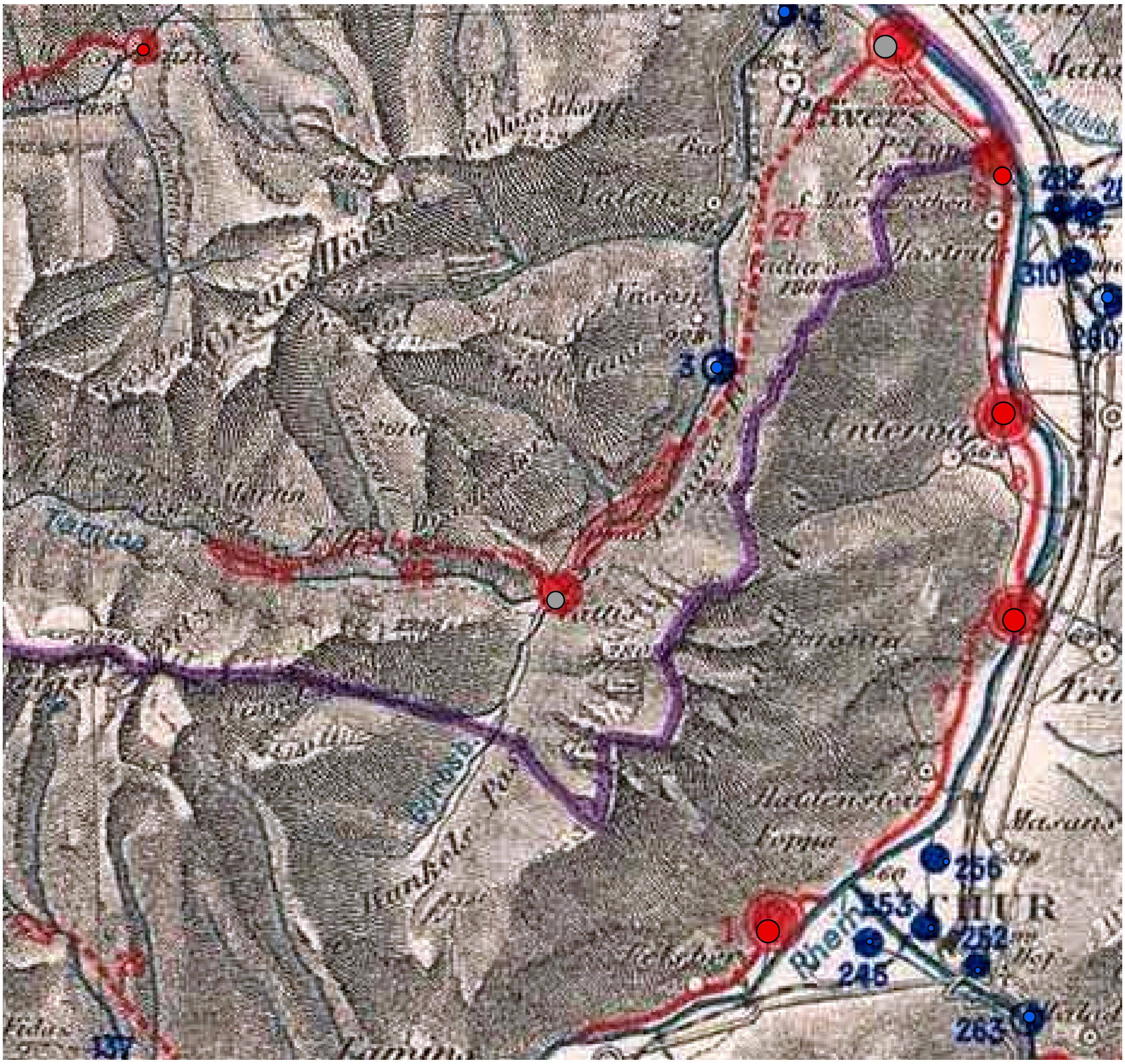
Notes: The map shows the existing and potential waterpower plants in Switzerland in 1914. Blue dots represent existing and red dots represent potential waterpower plants. Both using available natural water sources. Grey dots represent existing and potential waterpower plants that require the building 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 the size of the dot: a minimal power of (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

with the individual coding is illustrated in Figure C.4. The map provides the corresponding waterpower for existing and potential waterpower 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 categories its respective lowest value is used to construct the waterpower potential. The map measures power for existing and potential waterpower plants based on constant minimal kW (based on 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. These existing and potential waterpower plants marked with blue and red dots in Figure C.3 correspond to the locations of potential waterpower plants presented in Figure 1 in the main text.

C.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 Kuznets 1957; Kuznets 1973). I collect this data from the Swiss Census focussing on employment across agriculture, manufacturing and services for the years 1860, 1880, 1900, 1920, 1941, 1955, 1965, 1975, 1985 and 2011 (see Bundesamt für Statistik 1860-

Figure C.4: Extract from historic map of potential waterpower



Notes: The figure shows an extract of the map from Bossard (1916) of exploited and potential waterpower in Switzerland in 1914. In the map blue dots represent exploited waterpower, red dots represent potential waterpower. The sites are represented in 5 categories: a minimal power of (i) small circle representing 20-99HP, (ii) half filled big circle representing 100-999HP, (iii) filled big circle representing 1000-4999HP, (iv) filled circle with orbit representing 5000-9999HP and (v) square representing above 10000HP. 1HP is equal to 0.75kW. 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 follow the original coding of sites (represented by the overlying circles) apart from cases where an embankment dam is required. This is denoted in the map by a red (blue) shaded area for potential (existing) dams. All sites requiring a dam are coded as a grey dot instead of their original colour, including sources that are partly supplied without a dam. Numbers associated with dots refer to additional data provided in additional tables for existing and potential waterpower plants. Purple lines represent administrative boundaries.

2011).[76] These provide information on employment of individuals for the whole of the

[76] 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.

Swiss population at the district level. Further, I collect information on manufacturing sectors for the years 1880, 1900, 1920[77] and 1975 identify 7 consistent industry groups:[78] "Electricity generation", "Construction, wood & stone products"[79], "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 become of 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.[80] Figure C.5 depicts employment shares in agriculture, manufacturing and services for the time-period 1860-2011. The figure highlights that up to the 1950s a transition from agricultural to manufacturing employment occurred with the share of services employment having remained broadly stable. After the 1950s, the service sector share of employment increased while the share of agriculture and manufacturing in employment declined.

C.3 Other data sources

To analyse the channels through which the effect of early electrification persists I collect data on electricity usage for 1929 and 1955 from the census (in **?**) to analyse 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

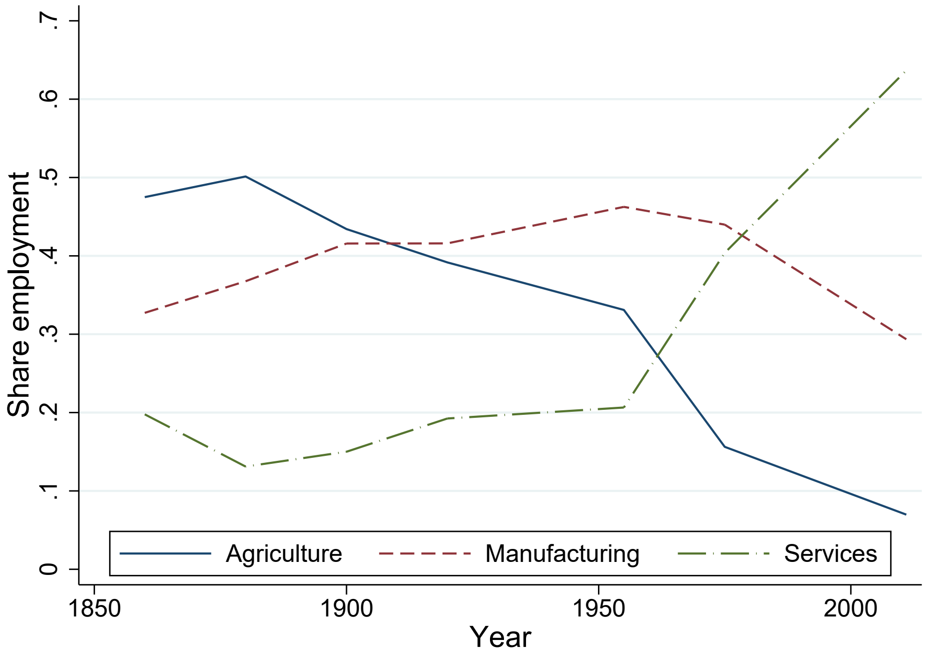
[77]For 1920 only information for 124 out of 178 districts were collected so far from the historical sources as it was impossible to obtain the remaining volumes required due to the current COVID-19 situation.

[78]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") in 1880, which was matched to "Others". So that employment in both had to be matched to "Others" in 1900 despite employment in paper stock having been part of "Chemicals" in 1880. These discrepancies were impossible to resolve without losing an exorbitant amount of detail through further aggregating the 7 consistent industry groups, e.g. through aggregating the categories "Chemicals" and "Others". However, this should only create measurement error as the initial distribution of employment in 1880 should be unrelated to the instrumented adoption of electricity.

[79]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.

[80]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 district in 1924, Arbon to Bischofszell in 1935, Moudon to Echallen district 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 C.5: 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 of employment reported is the average across the 178 districts in the sample. Sources: Bundesamt für Statistik 1860-2011

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 C.2. 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.

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 C.2: 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 science investment, government infrastructure investment, certain taxes, and the building and regulation of waterpower plants for electricity generation. I aimed at selecting the first 6 referendums that focus on an as clearly defined issue as possible and are comparable over time. For referendums on government investment in education and science I focus on expenditures, but do not include referendums focussed on the redistribution of power across different levels of administration. For government infrastructure subsidies On infrastructure referendums 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.