Innovation, Interconnection, and Institutions: Evolving Electric Power Systems in the Early 20th Century

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Abstract: This paper examines the evolution of electric power systems from their earliest days in the 1880s through World War I and the barriers to achieving interconnected distribution systems. In the very earliest days of electricity, there were no gains to interconnection. Beginning in the 1910s, interconnection of independent distribution systems would have offered lower cost and higher reliability. Coordination costs and the transactions costs acted as barriers to achieving this. World War I generated electricity demand far outstripping supply in some locations, such as Niagara Falls and the Pittsburgh region. The problems associated with excess demand led the military to intervene. Military engineers worked with electricity companies to rationalize generation, interconnect transmission networks, and plan new investment so that war-related production could be maximized. Military intervention temporarily lowered the coordination costs and transaction costs associated with state public utility commissions and allowed regional interconnection in selected areas. The tension between regulation-induced transaction costs and coordination costs and the benefits of interconnection persists to this day.

Note to NU Searle workshop participants: This draft focuses on the historical narrative. We have some applied theory and data analysis planned but not implemented that are not reflected here, but that I'll describe in our discussion. I look forward to your comments.

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I. Introduction

The United States entered World War I in April, 1917. In the summer of 1917, manufacturing war supplies and munitions was causing power shortages and rolling blackouts in urban industrial centers like Niagara Falls, Buffalo, Pittsburgh, and Youngstown. Electrical systems and technologies had advanced so much since the late 1880s that many industries had switched to electric motors for their motive power, and even industries with production processes that relied primarily on coal (e.g., steel) used electricity in their factories. By 1917 many homes, especially in urban areas, had electric service (United States Department of Commerce 1917, Table 24). Many states had also implemented public utility regulation, so the prices paid by both industrial and residential customers in those states were fixed by law.

From this perspective, the problem in 1917 seemed to be an increase in the demand for coal beyond what was readily available. Coal was an input in both electricity generation and steel manufacturing. In steel it had no meaningful substitutes, but in electricity generation the main substitute for coal was water — if the transmission lines existed to transport the power from the hydroelectric source into the local distribution system.

The urgency of the war effort and power shortages prompted Charles Keller, chief engineer in the War Department, to send Robert J. Bulkley to investigate circumstances in these urban areas; Bulkley soon sent investigators to other regions of the country. Keller's thorough report, *The Power Situation During the War*, provides detailed case studies and data on insufficient electricity and blackouts in 1917.

Keller's top recommendation was more interconnection across geographically dispersed distribution systems using high-voltage transmission lines. Interconnection of systems with load patterns that were not perfectly correlated would make more generation capacity available to each utility at any given time, and if used, would increase capacity utilization and capacity factors. But if distribution systems were already operating at high capacity factors, or if utilities had highly correlated load patterns, system interconnection might not alleviate the power shortages and blackouts.

Why was there so little interconnection between distribution systems pre-World War I? World War I was an unanticipated exogenous shock that generated demand for electricity far outstripping supply in locations such as Niagara Falls and Pittsburgh. The problems associated with excess demand led the military to intervene. In Niagara Falls and Buffalo the primary focus was on installation of additional hydropower and negotiation with Canada to receive larger amounts of electricity from their Niagara Falls generation capacity. In Pittsburgh, military personnel worked with electricity companies to rationalize generation, since some small and relatively inefficient plants were still in operation. Further, there were opportunities to interconnect plants from Pittsburgh northeast to Youngstown and Cleveland. New investment was planned during the war, but very little of this capacity was built until after the war, if all. Military intervention temporarily lowered the transaction costs among companies, since the military organized several meetings of regional companies, facilitated acquisition of rights to build transmission lines connecting Pennsylvania and Ohio, and compelled the state public utility commissions to cooperate.

After the war some interconnection did occur in different parts of the country in the 1920s and early 1930s, often through regional holding companies (Neufeld 2016). Holding companies had incentives to create integrated systems to realize economies of scale and scope. Unfortunately the financial excesses of the holding companies led to limitations on their expansion and in some cases dissolution under the federal Public Utility Holding Company Act of 1935. State regulation proved to be a significant barrier to large-scale regional integration. Public utility commissions had little incentive to promote integration if it required sharing regulatory power with other commissions; it was easier for firms to maintain excess capacity. Transaction costs fell again in the run-up to World War II, when mounting war-related demand for electricity and a southern drought led to federal intervention and creation of a seventeen-state power pool.

Interconnection was happening pre-WWI, but it did not take the contractual form at the transmission level that Keller had in mind. Interconnection occurred through distribution system acquisition. In cities like Chicago and New York before regulation, competition among multiple electric lighting companies was vigorous and successful firms acquired failing rivals. In addition to such consolidation on the intensive margin, urban utilities like Commonwealth Edison in Chicago acquired distribution companies in adjoining communities, expanding on the extensive margin. Acquisition provided an alternative to contracting for system interconnection.

In this paper we use Keller's recommendation and analysis as a motivation to analyze the organizational and institutional framework in which interconnection happened in the early decades of the electricity industry. Interconnection can happen through one of two means: acquisition or contract. By 1905 high-voltage transmission technologies had advanced sufficiently that, at least in theory, distribution systems 500 miles apart could be connected using transmission. Interconnection was thus technologically feasible by WWI, but was underutilized as a capacity expansion strategy relative to acquisition and internal investment.

We analyze the interconnection question with a focus on transaction costs and how they affect utility investment decisions. World War I was an exogenous shock to both the production and consumption of electricity of a magnitude larger than anticipated by those doing capacity planning in distribution systems. Couple that exogenous shock with the idea that electricity transmission is a thorny contracting problem – alternating current electric systems mean that the physical flow of power is never guaranteed to match the contract path, which makes contracting difficult, especially when combined with the potential for multiple parties and the absence of precise metering and measurement technologies at the time. State regulation exacerbated this situation by reducing interstate interconnection incentives at the margin and focusing the investment incentives of regulated utilities on expanding the capacities of their own distribution systems. In 1918 military intervention temporarily lowered some transaction costs, since the military organized several regional meetings, facilitated acquisition of rights to build transmission lines connecting Pennsylvania and Ohio, and compelled the state public utility commissions to cooperate.

Thus the research question in this paper is*: as firms consolidate and interconnect through acquisition, what is the effect on capacity utilization, and does the WWI intervention change the use of contractual interconnection relative to the pre-war period*? We analyze state-level data on generation capacity, total generation, number of firms, and firm size, from the *Census of Electrical Industries*, collected every five years 1902-1937.

At the margin utilities facing a make-or-buy decision chose investment in expanding their own distribution system capacity rather than interconnecting. Here we explore three hypotheses for the dearth of pre-war interconnection:

- *Excess capacity hypothesis:* Utilities had built sufficient excess capacity at the intensive and extensive margins to absorb the increase in electricity demand from foreseeable demand shocks.
- *Utility incentives hypothesis:* Utilities had little incentive to interconnect because they wanted to retain operational control and competed with each other in a market for industry location.
- *State regulation hypothesis:* The implementation of state public utility regulation in 1911-1914 in Ohio and Pennsylvania reinforced utility incentives to expand distribution systems and thus introduced a new transaction cost in the market for interconnection.

We find little evidence that the technology was still a barrier to interconnection by the mid-1910s, although high copper wire prices in 1916 and 1917 may have been a factor. The historical development of regional interconnection is consistent with the hypothesis that state-level public utility regulation introduced transaction costs that prevented multi-state interconnection when it would otherwise have been efficient, reinforcing the utilities' preferences against interconnection.

The slow and sometimes forced adoption of interconnection resulted from the interaction of technology, transaction costs, and institutions, and how those factors shaped the incentives of utilities and regulators. Our analysis of the interplay of electricity technology and institutions draws on a substantive literature, much of which examines the origins of state public utility regulation in the early 20th century. Jarrell (1978) constructed a public choice analysis of the origins of state regulation using the Stigler (1971) and Peltzman (1976) models of demand in the market for regulation. Jarrell argued that the demand for state regulation arose both from the Progressive/public interest impetus to reduce corruption and lower prices and from the industry's desire to restrict entry and lower their cost of capital. Lyon and Wilson (2012) expand on Jarrell's analysis using investment data to show that state regulation reduced the propensity to invest, a result consistent with regulatory capture by electric utilities. Knittel (2006) examined the origins of state regulation using Priest's (1993) theory of regulation and incomplete contracting; his proportional hazard model suggests that the move to state regulation resolved some contracting inefficiencies and increased investment (a result that is in tension with Lyon and Wilson). Neufeld (2008) used a discrete hazard model to test the Stigler-Peltzman-Jarrell interest group theory of regulation; he found that the move to state regulation reduced municipal hold-up and appropriation of the appropriable quasi-rents of utility investments. These works provide careful and thorough historical, theoretical, and empirical analyses, and we build upon them in our focus on the role of transaction costs and institutions in the pattern of distribution system interconnection in period surrounding World War I.

The paper proceeds as follows. Section II describes the electricity supply constraints in the buildup to World War I and the War Industries Board's recommendation for increased interconnection. Section III explores the evidence for the hypotheses stated above and presents an analysis of national and state-level data on capacity utilization. Section IV presents a case study of the Pittsburgh region's supply constraints during World War I that illustrates and adds detail to support the coordination and contracting cost argument. Section V briefly discusses transaction costs, contracting costs, and coordination costs within the broader historical narrative, and Section VI concludes.

II. The Power Situation During the War

In 1915 the electricity industry was growing by taking advantage of technological change and the financial stability introduced by its newly-regulated status. By 1915 the electricity industry in the industrial "early adopter" states (e.g., Illinois, New York, Ohio, Pennsylvania) was characterized by geographically contiguous regulated, vertically-integrated monopolies with sufficient capacity margins to enable them to provide reliable service to their residential, commercial, and industrial customers, to electric railways, and to municipalities for public lighting and other public works.

World War I was building in Europe at the same time. Woodrow Wilson campaigned for President in 1915-1916 on a platform of military and diplomatic neutrality, despite the German sinking of the British passenger ships the *Lusitania* and the *Arabic* (with substantial American casualties) in May 1915. In May 1916 German authorities agreed to stop attacking passenger ships, although they continued submarine attacks on cargo ships. Although in 1914-1916 the U.S. had not entered the war, U.S. manufacturers were supplying munitions to Britain and France; export demand from Britain and France for munitions to support their war effort increased well before the U.S. entered.[1] To achieve defense policy objectives of meeting this export demand while also enabling the US to prepare for any entry into the war, President Wilson established the Council of National Defense in August 1916 to coordinate economic activity in support of the war effort.

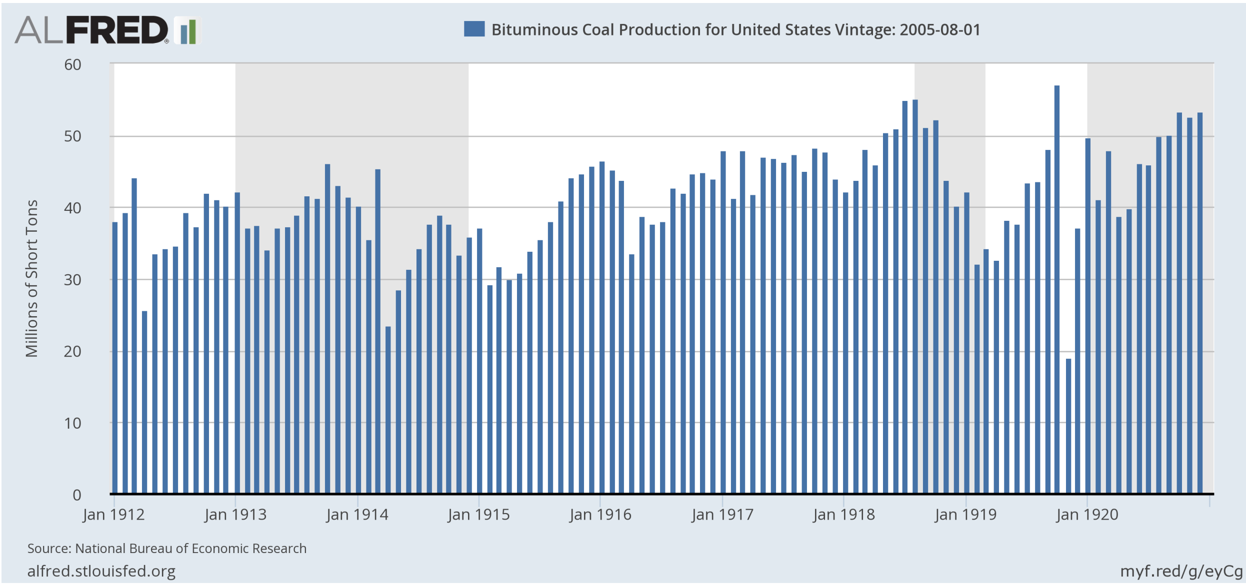
Once the preparation for US entry increased in 1916, domestic demand for munitions increased, shifting industrial production toward munitions and away from other non-war-related goods. German submarine attacks on passenger ships resumed in early 1917, based in part on the U.S. activity of supplying munitions to Allied forces. These attacks put pressure on President Wilson to ask Congress to declare war and enter the conflict. He did so on April 2, 1917, after naval intelligence revealed that German authorities encouraged Mexico to support the German war effort in return for German assistance in reclaiming territory lost to the United States after the Mexican-American War.

Preparation for war entry entailed increased manufacturing to supply the war effort, which meant increased use of coal. The increased output of steel products increased the manufacturing demand for coal in two ways: coal was the primary fuel for steel manufacturing at this time, and was also used as a fuel to generate electricity in locations with little or no hydroelectric power. In the Pittsburgh region utilities built coal-fired generation to serve industrial customers that had built factories in close proximity to the coalfields of western Pennsylvania and eastern Ohio to economize on transportation costs. War production not only increased manufacturing activity in this region, but also increased it elsewhere, and by mid-1917 coal mined in the region was shipped to other areas, which also changed the spatial allocation of rail cars. By October 1917 the U.S. government admitted that there was a general coal shortage in the country (Chicago *Tribune*, October 21, 1917; United States Senate 1918).

Figure 1 shows monthly bituminous coal production 1912-1920. The pattern shows low production during the 1913-1914 recession and the general increase in the 1916-1917 period with the increase in war production. Coal production is low December 1917-February 1918, reflecting the loss of production associated with the unusually harsh winter weather and the transportation problems that exacerbated the coal shortage that winter.

[1] Rockoff 2004.

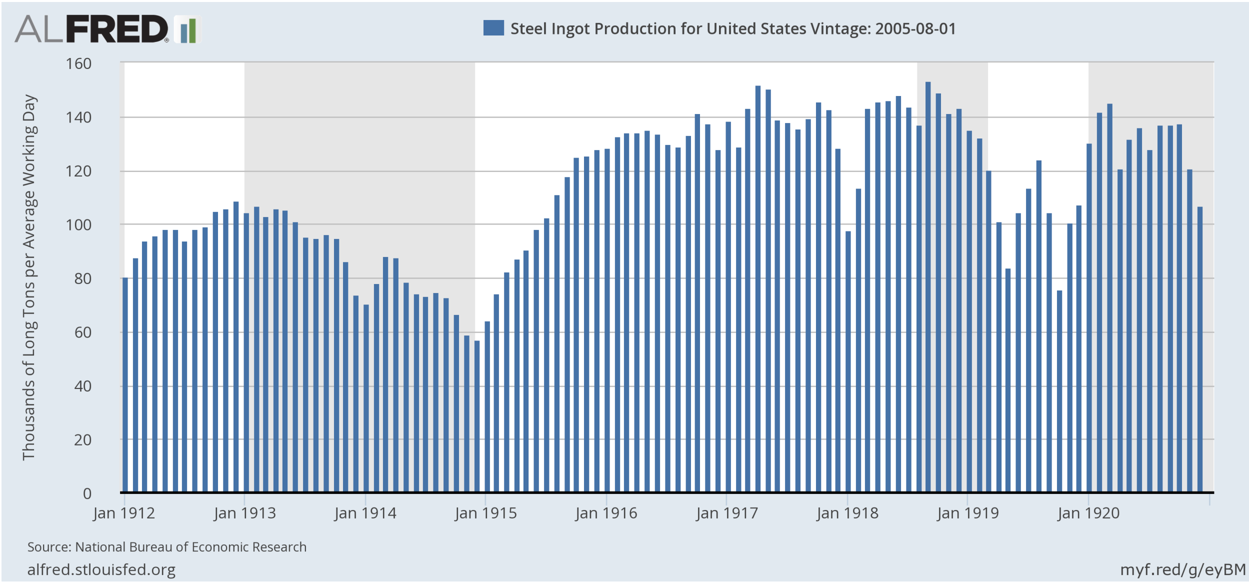
Figure 1. Bituminous Coal Production, Monthly, 1912-1920



[ADD COAL CAPACITY UTILIZATION CALCULATION]

One important increased use of coal was in producing a variety of steel products used in manufacturing, construction, and then in the war effort – steel ingots, billets, bars, rails, and beams, steel tank plates, and wire rods and nails (Berglund 1918, p. 599). After the 1913-1914 recession steel demand increased for use in manufacturing and construction. Figure 2 shows the monthly production of steel ingots (the basic intermediate-stage steel product) 1912-1920. The observations for 1916-1918 reflect the initial demand increase for the allied war effort, the increase with US entry into the war in April 1917, and the loss of production associated with the harsh weather, transportation problems, and coal shortage December 1917-February 1918.

Figure 2. Steel Ingot Production, Monthly, 1912-1920



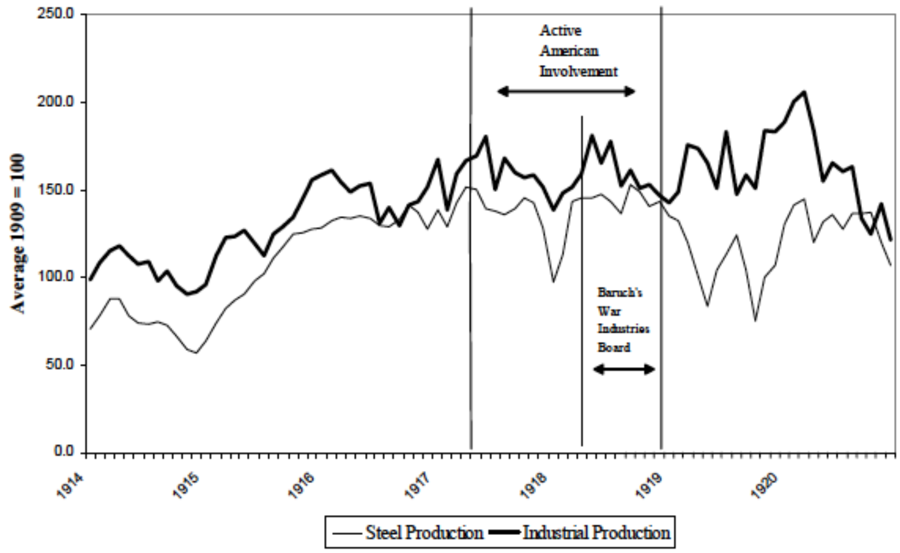
Such an increase in steel production increased the demand for electricity in the steel-focused regions of western Pennsylvania and eastern Ohio (Keller PAGE NUMBER).

[ADD STEEL INGOT CAPACITY UTILIZATION]

Net ton = US ton = short ton = 0.892857 long ton (aka Imperial ton)

Similarly, Figure 3 from Rockoff (2004) shows the increase in steel production and in the Miron-Romer index of industrial production during World War I, particularly in 1917 and beyond, once the US entered the war. Achieving this increased level of industrial production required an increase in electricity production, and given the long construction times in generation capacity that make electricity supply somewhat inelastic, this increased production would result largely from increases in capacity utilization rates, or load factors.

Figure 3. Steel Production and Industrial Production Around World War One



Notes: Rockoff (2004), p. 28.

Both the export-driven and the domestic shifts in the munitions demand curve increased the demand for electricity for industrial production. In systems with considerable excess capacity, such a demand increase would be met with little change in reliability to other customers and with little need to prioritize use of scarce capacity. Census data suggest that the electricity industry in general was operating with substantial excess capacity (as we demonstrate in Section III), but the pressures of increased war production strained systems in industrial areas and in urban areas with dense populations and large shares of industrial activity.

These strains came to the attention of the War Industries Board, which had been established in July 1917 to coordinate the purchase of war supplies more directly than the Council of National Defense. In his subsequent report to the Secretary of War, *The Power Situation During The War*, engineer Charles Keller observed that although the two agencies

> … had early taken cognizance of many fundamental matters such as railroad transportation, coal production, supply of basic materials such as copper, lead, zinc, … neither of these agencies took any steps for the ascertainment of our exact resources in electrical power and for the adoption of a policy to govern the assignment of existing supplies and the procurement of necessary increases. (1921, p. 1)

Several industries that substituted into producing military supplies (e.g., electrochemical firms) were concentrated near Niagara Falls and Buffalo, New York, taking advantage of the large generation capacity of the combined American and Canadian hydroelectric utilities located there. Demand growth in 1915 due to war orders from Britain, France, and Russia strained generation resources around Buffalo and Niagara Falls, and by 1917 no excess capacity remained from the hydroelectric plants. This lack of electricity became a binding constraint on the production of war products.[2]

The War Department sent Robert J. Bulkley, chairman of the legal committee of the War Industries Board, to investigate the electricity constraints near Niagara Falls and in other crucial centers of population and industrial activity. He and his staff performed regional field investigations to catalog existing electricity supply resources (generation, transmission, and distribution), identify pressure points and gaps where insufficient capacity was a constraint on war production, and propose and implement measures to eliminate these constraints. In several regions, particularly the Niagara region and western Pennsylvania-eastern Ohio, some generation capacity was underutilized because transmission infrastructure did not enable generation plants in one utility's service territory to send energy to industrial customers in an adjoining utility's service territory. Bulkley claimed that the lack of interconnection was a constraint that left some resources underutilized and some customers involuntarily curtailed. The mission of the War Industries Board was to identify and remedy such instances of inefficiency in infrastructure that hampered the war effort.

By November 1917 Bulkley had completed his initial analysis; his proposals included curtailment of service to "nonessential customers", increases in generation capacity, and increased interconnection through transmission investment and construction to enable energy generated at underutilized plants to be used by industrial facilities in neighboring regions. The Niagara region was the War Industries Board's initial target, and it created a model they employed in other regions for similar situations: survey the territory in detail, prepare a "priority policy" to implement when curtailment is necessary, and develop a plan to increase the power supply based on the survey.[3] With respect to interconnection Keller states:

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[2] Keller 1921, p. 3.
[3] Keller, p. 9.

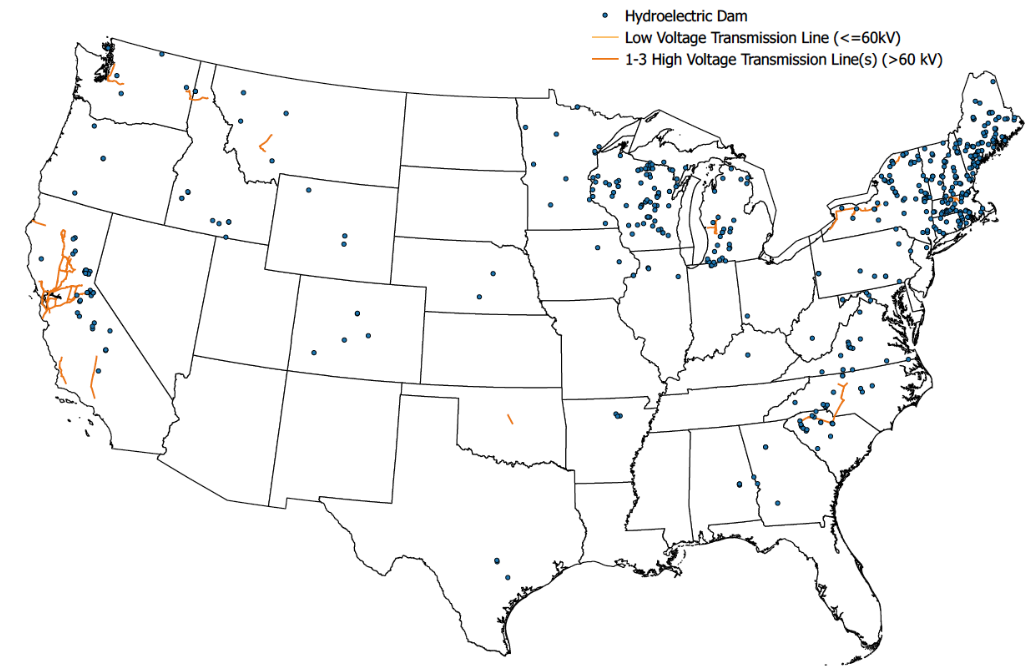
> Interconnection of adjoining systems by comparatively long transmission lines will be included in both the short and long time provisions, with a view to taking advantage of unused capacity, diminishing the total reserve held idle, and utilizing power released by the diversity often existing in the incidence of demand in even adjoining districts."[4]

These first three of the five steps in their model identify the role that interconnection could play in increasing utilization rates and reducing involuntary curtailment of service, both to war-essential and nonessential customers.

Very few utilities in manufacturing areas were interconnected before the war. Figures 4 and 5 show the number of high voltage ("high tension", greater than 60kV) transmission lines in 1908 and 1918. In New York in 1908 high-voltage transmission connected Niagara Falls to Buffalo (20 miles) and ran along the Erie Canal east to Rochester and Syracuse. In the western New York-Pennsylvania-eastern Ohio region, the most notable difference in transmission lines between 1908 and 1918 is the increase in transmission capacity between Pittsburgh and Youngstown. Note also the increase in hydroelectric dam construction evident in Figure 5, particularly in western Pennsylvania, western Ohio, and central New York.

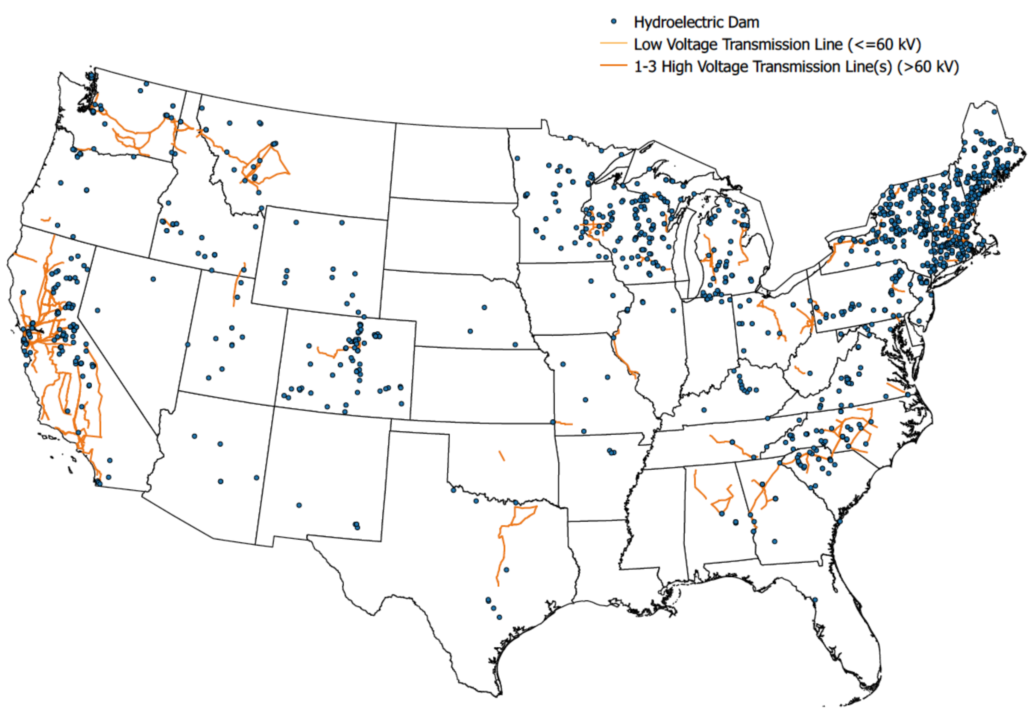
[4] Keller, p. 9.

Figure 4. Transmission Capacity and Hydroelectric Dams, 1908



Notes: Gray (2017)

Figure 5. Transmission Capacity and Hydroelectric Dams, 1918



Notes: Gray (2017)

III. Development of Electric Power Systems: Why So Little Interconnection?

Here we develop and transaction cost economics framework for understanding the organizational choices in electricity interconnection leading up to WWI. Make-or-buy logic underpins transaction cost economics theories of integration (Klein, Crawford, & Alchian 1978, Masten 1986). When transaction costs are sufficiently large, contracting is costly between independent firms. One implication of high transaction costs for contracting is hold-up when production involves relationship-specific assets — if a contract requires a firm to invest in relationship-specific assets but transaction costs make contracts incomplete and/or difficult to enforce, then a firm can extract rents from its contracting partner that makes an irreversible specific investment. When contractual relationships are prone to hold-up and transaction costs are high, less-than-optimal exchange and production occur. One way to mitigate this cost is through merger of the two firms into a single firm. Such integration is an organizational choice that enables firms to internalize benefits and costs of production while avoiding transaction costs.

The key feature of the make-or-buy model of integration is asset specificity. Williamson (1983) provides a taxonomy of four types of asset specificity: site or location specificity, physical specificity of the asset to the transaction, human specificity of the human capital to the transaction, and dedicated specificity of investments made to fulfill specific transactions that would not have been made otherwise. ELABORATE

The make-or-buy model of mergers can help us understand early electric system interconnection. Consider a model in which firms enter local markets and build local, low-voltage distribution networks to serve electric lighting customers. Rival firms within the local market compete, and consolidation occurs through acquisition when higher-cost firms cannot profit as economies of scale and scope arise with technological change. The newly-consolidated firm interconnects the previously unconnected *distribution* networks, incorporating or eliminating duplicate wires; call such interconnection *intensive margin* interconnection. Economies of scale and scope reinforce this consolidation, culminating in a single-firm monopoly utility. Adjoining monopolies serve non-overlapping markets. To achieve lower costs and/or higher revenues these adjoining monopolies can merge, or a larger firm can acquire an adjacent smaller firm, interconnecting their distribution systems; call such interconnection *extensive margin* interconnection. One observable outcome of either intensive or extensive interconnection at the distribution level would be increased capacity utilization.

The alternative way to increase system capacity is contractual, through interconnection with another distribution system using high-voltage transmission and having the firms retain independent ownership. Distribution system interconnection using high-voltage transmission would require investment in and construction of transmission lines connecting the two systems, and a contract between the two firms would have to stipulate how they would share responsibility for the investment and what rights they would each have to use the network and call on the other firm to provide power. Such an investment would be relationship-specific in all four of the ways that Williamson described — the wires network would be site-specific, involve physical and human capital specific to electricity transmission and difficult to transfer to other uses, and once built would be dedicated to that specific transaction.

Early electric utilities followed an acquisition interconnection strategy of low-voltage interconnection of overlapping (intensive margin) and adjoining (extensive margin) firms through mergers and acquisitions. By the 1930s, though, system interconnection had increased.

Three economic reasons can help us understand why electric utilities would choose acquisition interconnection rather than contractual interconnection, even in the face of the high demand and shortages during World War I. The industry's pre-war history shows how firms developed the self-contained vertically-integrated distribution systems prevalent in 1917, an architecture that state-level regulation reinforced starting in 1907. Within the historical narrative below we examine three economic hypotheses for the lack of interconnection in 1917.

Utilities could have looked at the required investment to build the transmission lines, and given their pre-existing excess capacity they could have deemed the investment not worth it for anticipated demand growth other than this unexpected exogenous shock.

Excess Capacity Hypothesis. Local distribution systems in urban manufacturing centers had sufficient capacity/enough reserve margins/low enough capacity factors that utilities had created through investment and acquisitions. But the magnitude of the increase in demand due to the war effort strained reserves in these non-interconnected systems.

Another important incentive comes from the likelihood that urban utilities such as those in Pittsburgh and Youngstown, while not competing directly for the same end users, were rivals in a market for firm location. As manufacturers decided where to site factories, electricity prices and quality of service would have been important margins on which firms in rival locations could compete, so they would be unlikely to want to interconnect with their rivals in such a market.

Utility Incentives Hypothesis. Utilities had little incentive to interconnect because the reliability benefits of interconnection were less than the costs of strengthening competing utilities in a market for industry location, so they invested instead in expanding their own distribution capacity to provide reliability.

Finally, after the commencement of state-level public utility regulation, such regulation changed the investment incentives of utilities and reinforced a local, within-state investment strategy. Other things equal, at the margin this emphasis would shift investment away from interstate interconnection and toward within-state distribution system expansion or consolidation through acquisition.

State Regulation Hypothesis. At the margin state PUC regulation creates a barrier between interstate and intrastate investment projects, reducing incentives for utilities in different states to contract with each other for interconnection purposes.

A. Creating a New Industry, 1880-1917: Technology and Policy

The commercial electricity industry and electric distribution systems originated with local electric light companies. In the early 1880s the "commercial application of electric technology unleashed a tremendous demand for more light."[5] City councils approved multiple simultaneous and overlapping franchises, so self-contained rival electric light firms often competed within cities to meet this growing demand. In Chicago, for example, at least 24 central station electric

[5] Platt 1991, p. 40; see also Hughes 1983 and David 1990.

companies started operations between 1887 and 1893.[6] These systems were small-scale both in size and in geography, expanding up and out through incremental innovation, demand growth, and consolidation of firms in the industry.

Economies of scope from using generation for industrial customers and electric railways turned early electric lighting companies into power and light companies. Early entrepreneurs (most notably Commonwealth Edison's Samuel Insull) wanted to increase demand by increasing electrification while reducing average costs, thereby enabling them to price their services attractively. As early as 1890 motors using direct current (DC) were beginning to substitute for steam power in driving small machinery.[7] These early motors simply replaced steam engines in belt-driven manufacturing processes, but a larger and substantively different change followed the invention and subsequent adoption of the alternating current (AC) induction motor, invented by Nikola Tesla in 1888. By 1909, electric drive and induction motors in factories had increased to 25 percent of capacity for driving machinery.[8] Induction motors directly driving machinery first displaced belt-driven machinery in industries like printmaking, electroplating, electrochemicals, electric furnace and machinery, and other electrolytic industries. Over the first three decades of the 20th century the steel industry also electrified by applying these and related technologies.[9]

In the 1890s development of higher voltage AC transmission technologies had reinforced the ability to construct generation at longer distances from population centers, but this was still a system with meaningful physical constraints on how the grid had to operate. Through the first decade of the 20th century increases in generator capacity and efficiency meant that electric companies experienced even more substantial economies of scale from building large-scale generation outside of cities and using AC transmission wires to transport it to consumers on lower voltage distribution networks in cities, although the lack of centralized dispatch in distribution systems before 1923 provided another constraint (Denny and Dismukes 2002). In the 1910s most independent utilities were not yet interconnecting with each other.

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[6] Platt 1991, p. 55.
[7] Platt 1991, p. 56.
[8] Devine 1983, pp. 358-359; see also Platt p. 107. Neufeld (2016) pp. 80-85 for a discussion of the induction motor adoption lag as a result of having to reconfigure factory floors spatially to accommodate and make the best use of them.
[9] Rogers 2009, p. 193.

Another important part of the technological system for high-voltage transmission and interconnection was the ability to convert between alternating current (transmission and some distribution systems) and direct current (many distribution systems). Charles Bradley, working independently from both Edison (direct current) and Westinghouse-Tesla (alternating current) developed and patented a rotary converter in 1888; the "… implications of the rotary converter made their practical and commercial impact felt in the United States, not instantaneously, but, progressively over the course of the 1890s, … by the middle of the 1890s devices were developed to convert in any direction" (David & Bunn 1989, p. 182). David and Bunn characterize the rotary converter as a "gateway technology" that operates independently of two systems and enables them to interoperate.

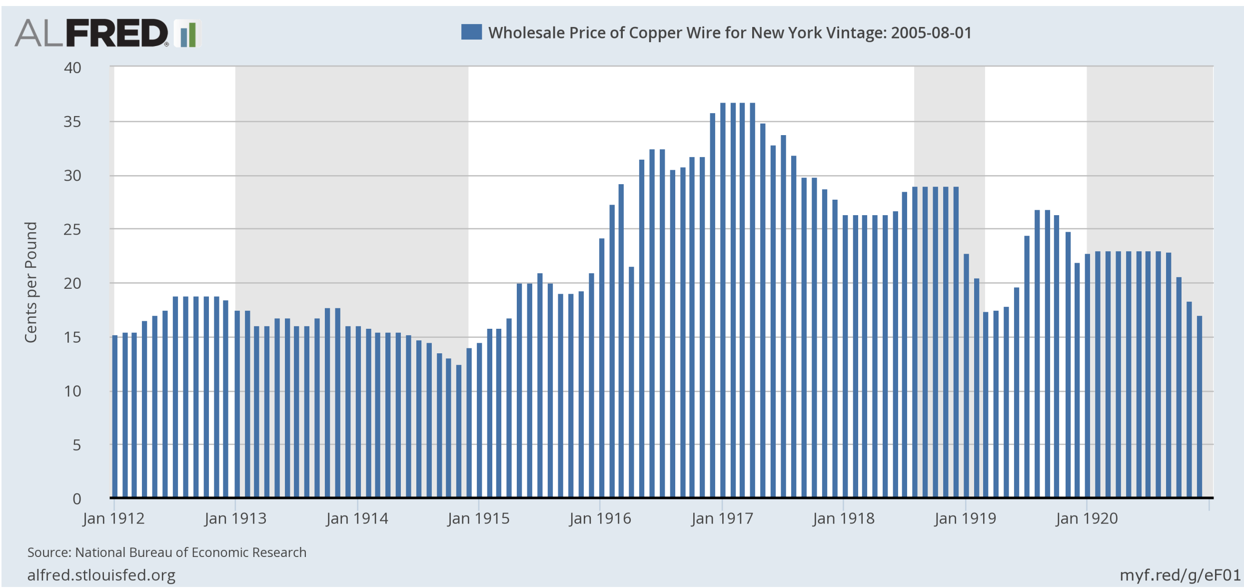
The engineering estimates at the time suggest that by World War I, interconnection via long-distance transmission had been technically feasible and economical for nearly a decade. Mershon (1905) provides engineering and economic estimates based on existing technologies, noting that those technologies were likely to change in ways that would make transmission feasible and economical over even longer distances. His analysis begins by laying out the economic calculation behind the decision of whether or not to build transmission:

> The elements which, in the broadest sense, limit the distance to which power can be economically transmitted, are two; the cost of power at the generating station, and the price which can be obtained for the delivered power. The difference between these two elements must cover the cost of transmission, the interest on the investment, and the profit. The cost of transmission comprises the loss of power in transmission, the cost of operating, and the cost of maintenance and repair. The value of the sum total of the interest which must be paid upon the investment, and the minimum profit which is considered satisfactory, will have much weight in determining the limiting distance of transmission. The less this sum is the farther power can be transmitted; a low interest rate and a low rate of dividend will, therefore, be conducive to long transmissions. (1905, p. 411)

Mershon then performs an engineering and economic analysis based on a set of assumptions about these variables, and then varies those assumptions to perform a comparative statics/scenario analysis. His analysis suggests that as early as 1905 long-distance transmission was technically feasible and economically profitable depending primarily on the cost of the line conductor used, typically copper wire. Although novel and unproven, Mershon calculated a maximum economical long-distance high-tension distance of 500 miles (1905, p. 420). Niagara Falls-New York City (408 miles), Niagara Falls-Pittsburgh (238 miles), and Pittsburgh-Youngstown (66 miles) all fall within that technical-economic constraint.

Mershon's analysis suggests that transmission investment and distance are a function of the cost of copper wire. Figure 6 shows copper wire prices 1912-1920, reflecting an increase in prices in late 1916 accompanying the increase in manufacturing to supply the war effort before US entry. While suggestive, they do not indicate strongly that high copper prices would have prevented transmission construction before the war.

Figure 6. Copper wire prices, 1912-1920



B. Excess Capacity and Capacity Utilization

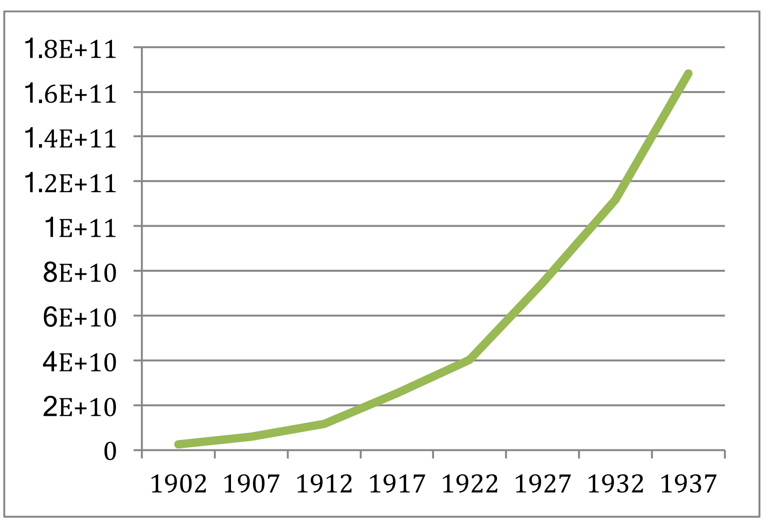
If utilities were investing in own-system capacity before the war, excess capacity due to acquisition interconnection and investment in their own distribution system would be an alternative to interconnection. National and state data suggest that utilities did have substantial excess capacity before the war, and that war production increased the demand for electricity and made use of excess capacity.

National Trends 1902-1937

The United States Bureau of the Census performed a special industrial census every five years 1902-1937 covering five electrical industries: central light and power stations, electric railways, telephones, telegraphs, and municipal fire alarm and police signaling stations. We use state-level data from these *Census of Electrical Industries* reports on central light and power stations to explore the early origins of electric power systems. These reports do not include any direct measures of reliability, so instead we focus on the reported data on the first of the two dimensions of reliability: sufficient generation capacity to meet demand in real time. Thus we look at excess capacity as measured by capacity utilization, with the benchmark of theoretical capacity if the installed capacity were in operation in every hour of the year.

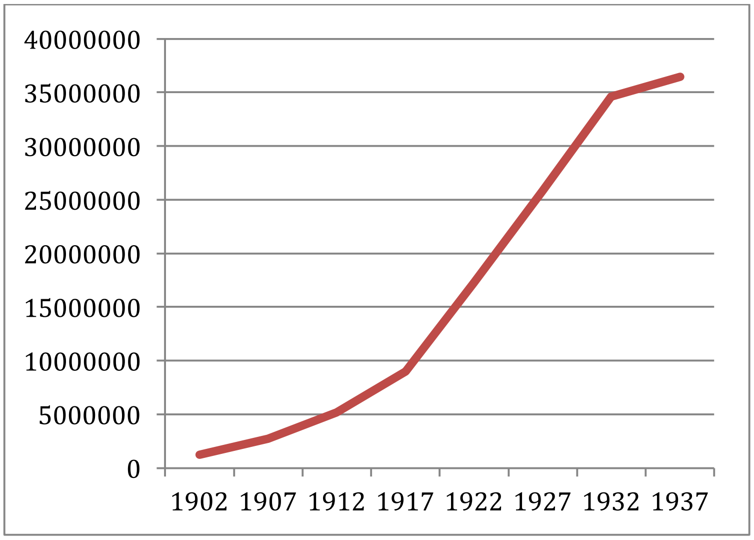
Between 1902 and 1937 electricity systems expanded dramatically, rapidly increasing the number of residential, commercial and industrial customers that were served in and around urban areas. Figures 7 and 8 display the annual U.S. figures for electricity consumption and capacity, respectively.

Figure 7. Annual national electricity consumption, kilowatt-hours, 1902-1937



Notes: Census of Electrical Industries

Figure 8. Annual national electricity generation capacity, kilowatts, 1902-1937



Notes: Census of Electrical Industries

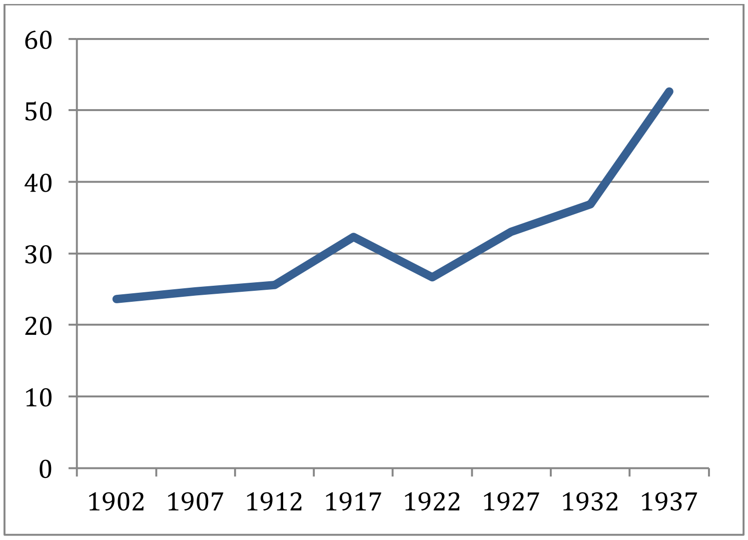
By themselves these data do not indicate the extent of excess capacity or of capacity utilization in the local distribution systems. We calculate a benchmark of theoretical capacity, or the output that would be generated if the installed capacity were running in every hour of the year, to evaluate the extent of capacity utilization. Table 1 and Figure 9 display the national aggregate annual utilization rates relative to this theoretical benchmark.

Table 1. Capacity utilization relative to theoretical capacity 1902-1937, national

Year	Utilization rate
1902	23.609
1907	24.701
1912	25.568
1917	32.286
1922	26.608
1927	33.031
1932	36.834
1937	52.664

Notes: Census of Electrical Industries

Figure 9. National capacity utilization rate relative to theoretical capacity, 1902-1937



Notes: Census of Electrical Industries

The aggregate annual utilization rate in 1902 is 23.61 percent, increasing to 52.66 percent in 1937. Low utilization rates in the early years of the 20th century are consistent with two main, and related, hypotheses: in the earlier years in the industry owners of distribution systems were building to create demand, and thus had not yet fully exploited the economies of scale and scope in the system; these systems were also stand-alone systems and not interconnected with other systems, even (or perhaps especially) in cities with multiple competing electric companies, so they did not have the advantage of using interconnection to increase their capacity utilization and hence their operating efficiency.

Even at an aggregated national level, these data suggest the effect that World War I had on the electricity industry. In 1912 output generated was 11.57 billion kilowatt-hours; in 1917, output was 25.44 billion kilowatt hours, a 120 percent increase. The capacity utilization rate was 25.6 in 1912 and 32.3 in 1917, a 26.3 percent increase, indicating the existence of pre-war excess capacity. These rates suggest that overall sufficient reserves existed, with some tightening in the run-up to World War I, but the experience recounted by Keller indicates that although the capacity existed, constraints such as lack of transmission and coal shortages prevented better, more efficient use of existing capacity.

State-Level Analysis

We also analyzed state-level capacity utilization rates relative to the theoretical capacity benchmark. Over the 48 continental states and the District of Columbia during the period 1902-1937, utilization rates ranged from 8.1 to 60.3, averaging 25.9 across all state-year observations.

Our analysis of excess capacity and interconnection focuses on "early adopter" states with urban areas having both dense residential population and concentrated industrial activity. Table 2 presents utilization rate data for four states: Illinois, New York, Ohio, and Pennsylvania. Across all state-year observations for these four states, the average capacity utilization rate was 29.4 percent.

Table 2. Utilization rates in electricity "early adopter" states, 1902-1937

	IL	**NY**	**OH**	**PA**	**Average**
1902	18.38	42.78	20.84	22.67	26.17
1907	25.52	34.39	19.61	22.37	25.47
1912	27.49	32.16	18.66	26.44	26.19
1917	*34.21*	*36.34*	*29.42*	*38.24*	*34.55*
1922	36.26	33.35	30.59	33.68	33.47
1927	34.07	35.85	30.94	8.39	27.31
1932	23.86	27.37	25.90	12.97	22.53
1937	38.38	36.77	42.28	40.80	39.56
Average	29.77	34.88	27.28	25.70	

Notes: Census of Electrical Industries

In all four states capacity utilization increased 1912-1917, with the most substantial increases in Ohio (18.66 to 29.42) and Pennsylvania (26.44 to 38.24). In Ohio the utilization rate increased by 57.7 percent 1912-1917, and in Pennsylvania by 44.6 percent. This increase pre-dates the efforts of the War Department to increase interconnection, which bore fruit in 1918 and were thus not reflected in the 1917 data.

C. Why Excess Capacity: Utility Incentives to Interconnect

Utilities operated with excess capacity pre-WWI, using that excess capacity as a buffer that provided a reserve margin and enabled them to achieve reliability and lower costs by exploiting economies of scale and scope. They could, however, have contracted for such reliability and had lower investment expenditure by sharing transmission investment with other utilities and interconnecting to take advantage of uncorrelated load patterns. Such contracting would have faced transaction costs.

Utilities making capacity investment decisions could choose among:

- *Own excess capacity* – investment was costly, but retention of competitive advantages and control were benefits
- *Interconnection* – lower investment costs because of cost sharing, get the benefits of reliability at a lower cost, but relinquish control
- *Develop nearby hydroelectric capacity* – possible in some locations, required hydroelectric generation and transmission investment

In this period, utilities choosing to expand their own capacity made economic sense for two reasons that we highlight: control and competition.

Utilities valued retaining operational control of their distribution systems (as they still do today). When considering the investment alternatives of own capacity or interconnection, own capacity gave them the benefits of retaining operational control, while interconnection relied on contracts and coordination with the operations of one or more other distribution systems. That transactional boundary between the firm and the market is a manifestation of transaction costs; transaction costs and incomplete contracting in this case would imply a loss of operational control under interconnection (Williamson 1979, Grossman & Hart 1986). NON-CONTRACTIBILITY

A second hypothesis for utilities preferring to expand their own capacity rather than interconnecting is that utilities competed with each other in a market for industry location. To the extent that utilities wanted to market their service in their territory as superior to other locations, they would perceive interconnection as lowering their rivals' costs (while also lowering their own). Competition in this market reduces the likelihood of interconnection. [NOTE: possible interesting Cournot model application here, asymmetric Cournot to account for differential economies of agglomeration?]

Developing nearby hydroelectric capacity was an outside option in some urban industrial areas, although hydroelectric dam development was typically more rural. Hydroelectric generation would have been a substitute for either coal generation capacity or interconnection, and in coal-rich areas before World War I and the coal shortage, the relative value of hydroelectric capacity was probably low and would also necessitate transmission construction.

[data and more analysis to come]

D. Why Excess Capacity: Regulation-Induced Transactions Costs in a Market for Interconnection

In this time period regulation was a nascent and increasingly important force shaping utility investment decisions. Economies of scale and scope created cost savings and led to consolidation among rival firms into one electric company owning and operating a local distribution system. Consolidation into single city-based firms raised Progressive movement concerns about monopolies charging high prices. The consolidation process occurred through debt-financed acquisition of assets from failing competitors. These motivations aligned incentives between policy makers and industry to implement state-level regulation, starting in 1907 with public utility commissions in New York and Wisconsin. State regulatory jurisdiction focused predominantly on two issues: siting approval for the construction of transmission and distribution wires, and determination of retail rates based on cost recovery and a reasonable rate of return. Implementing these regulations involved granting the utility a legal entry barrier and an obligation to serve all customers in a specified geographic service territory.

States with large cities and substantial industrial activity experienced earlier development of commercial distribution systems and adopted state-level regulation early compared with other states. Table 3 shows the years in which public utility commissions were established in "early adopter" states with concentrations of urban population and industrial activity: Illinois, New York, Ohio, and Pennsylvania.

Table 3. Date of public utility commission establishment, early electricity adopter states

State	Year PUC Established
Illinois	1913
New York	1907
Ohio	1911
Pennsylvania	1914

Notes: Stigler & Friedland (1962), Appendix A

By 1915 primary urban manufacturing centers in the U.S. – New York, Chicago, Pittsburgh, Philadelphia, Cleveland, Buffalo, for example – had regulated distribution monopolies with a single distribution system infrastructure.

A political economy model with transaction costs can help us understand how state regulation could, at the margin, reduce utility interconnection. Assume state regulators are interested in maximizing benefits to residents of their own state and in maintaining their own decision-making control over the investment choices of the utilities they regulate. This framing of regulator objectives, in combination with the profit-maximizing objectives of utilities, yields the following hypotheses:

Regulator-utility alignment: State regulation aligns with and reinforces existing utility incentives to increase investments in their own capacity by implementing rate-of-return regulation.

Regulator in-state priority: At the margin state regulation concentrates utility investment in within-state infrastructure, which would decrease interconnection with out-of-state utilities compared to in-state utilities.

These hypotheses suggest analyzing the processes of rate cases and the interaction between utilities and regulators in these early years. If both utility and regulator prefer retaining control and making in-state investments, and if utilities see these investments as giving them a competitive advantage in a market for industry control, they would support regulatory decisions that would increase their own-system capacity. In the interstate market for interconnection, though, state regulation created transaction costs by focusing both utility and policy attention on within-state choices that may have been more costly than interconnection alternatives.

An interesting potential testable implication of this theory is the development of hydroelectric capacity post-WWI. By 1918 significant numbers of dams in central Pennsylvania that had been built for other purposes were converted into hydroelectric dams (Gray 2017). Regulators supporting those investments but opposing Keller's arguments in favor of interstate interconnection would lend support to this theory.

[data and more analysis to come]

IV. Case Study: The Pittsburgh Region

Detailed evidence from Pittsburgh's manufacturing and electricity can indicate the potential explanatory power of our hypotheses. Demand for electricity nationally and in Pittsburgh was low in 1914 due to a recession from January 1913 to December 1914. In 1915 war-related orders from European countries began to arrive, leading to rapid increases in industrial production in Pittsburgh and the surrounding area including eastern Ohio.[10] Table 4 shows the dramatic increase in kilowatt-hours of electricity generated in the region. By the fall of 1917, the strains on electricity supply were becoming a problem. "Complaints were received by the Secretary of War in regard to conditions at and near Pittsburgh. At this place, the heart of the steel industry of the country and an important center in the production of coal, of heavy machinery, of railroad equipment, of electrical apparatus, and of rubber tires, a congestion of war orders and manufacturing had completely exhausted the power resources of the district."[11]

[10] "The principal manufacturing cities of the district are Pittsburgh, Connellsville [in Pennsylvania], Wheeling [West Virginia], East Liverpool, Steubenville, Canton, Massilon, Alliance, Akron, Warren, and Youngstown [in Ohio], and it is also an important coal mining region." (Keller p. 12).

[11] Keller, p. 11.

Table 4. Electricity generation in the Pittsburgh district, 1914-1917, kilowatt-hours

Year	Kilowatt-hour output (millions)	Increase in kilowatt-hours (millions)
1914	685.2	
1915	847.4	162.2
1916	1,192.0	344.6
1917	1,465.7	273.7
1918	1,662.9	197.2
Total		977.7

Notes: Keller, p. 92.

The initial strategies for addressing the electricity shortage in the short run were forms of rationing.

> The first complaints received by the Secretary of War were from the city of Pittsburgh to the effect that street railway schedules had been altered so as to diminish the number of cars and car trips, especially during the morning and evening hours, thereby inconveniencing the working and business people and causing public dissatisfaction, which was increased by the fact that an attempt had been made to place power consumers on a rotating or alternating schedule and to require them to remain idle at certain prescribed times. The importance of maintaining satisfactory conditions and of promoting the maximum possible output in Pittsburgh was such as to induce the Secretary of War to interest himself actively, and he therefore assigned Mr. Bulkley to make an investigation.[12]

Bulkley was head of the legal committee of the War Industries Board and so was well positioned to investigate and oversee negotiations with electric companies. Indeed, immediately prior to arriving in Pittsburgh in December 1917, he had been negotiating with the Canadian government to address power shortages near Buffalo/Niagara Falls.

Rationing was the logical economic response to increased electricity demand due to war production. The cost and the time involved in increasing generation capacity means that supply of electricity was relatively inelastic. On the demand side retail rates were fixed by contract, a custom reinforced and entrenched by regulation. As a result demand was inelastic, and prices could not adjust to clear the shortage, so rationing must occur.

[12] Keller, p. 11.

One of the first actions taken to prevent even greater electricity shortages in Pittsburgh and other industrial centers was the issuance or order prohibiting the placing of further orders with firms in the affected centers without permission of the War Industries Board. The Secretary of War issued the first such order on December 28, 1917, and a second order on March 25, 1918.[13]

The next action was prioritization of service, with an eye toward maximizing output of critical items and maintaining morale:

> Industries are arranged in four classes, graded in importance from class 1 to class 4—class 1 being those industries and plants of exceptional importance in connection with the prosecution of the war, their importance being so high that their requirements must precede those of the three remaining classes in order that they might receive their full allowance of power at all times. Except in extreme cases, all small consumers having a connected load of 100 horsepower, or less, were included in class 1. The possible saving in electric energy through curtailment of such small consumers would not justify the losses and industrial disturbances that would follow. Classes 2, 3, and 4 took preference in the order named.[14]

Class 1 comprised war-related and small residential consumption, but the 1917 shortages showed that even class 1 consumption strained the reserves of local distribution systems.

Pittsburgh's crucial role in war-related manufacturing made improvements essential. Major Lacombe, an Army Engineer, conducted a detailed study in early 1918 and proposed a plan to address the problems quickly. The plan was presented to the electric companies at a meeting in Washington in July, but they viewed financing construction as nearly impossible. Despite the inability to begin new construction immediately – although some new construction would later be started – other improvements were made. "A better cooperation and interconnection of the transmission systems was established between some of the main central station companies. This permitted a freer exchange of power between the systems, and though it did not increase the amount of power materially, a greater reliability of power supply was obtained, in that reserve capacity in one system was called upon during the shortage on other systems."[15]

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[13] Keller, p. 42.
[14] Keller, pp. 47-48.
[15] Keller, p. 138.

Because of the strain that had already been put on electrical generation, repair was a priority in Pittsburgh. "The comprehensive study of the situation showed, first, that the immediate danger at and near Pittsburgh was that the overtaxed plants of the Duquesne and West Penn Cos. would at some time be irremediably damaged. To obviate this danger a program was prepared for the progressive repair of those units that had already been damaged or that were in any way under suspicion, and this work was promptly inaugurated."[16] While some of the work had been completed, much remained to be done when the war ended in November 1918.

Another issue was the need to replace relatively inefficient plants to conserve on coal, which was expensive and in some periods difficult to obtain. "Coal consumption per kilowatt hour generated varies from 1.8 pounds in the efficient plants to 9.2 pounds in the older and less efficient plants. … If the power now generated by the inefficient plants in the western Pennsylvania and eastern Ohio district with a coal consumption rate of over 2.5 pounds per kilowatt hour and a power manufacturing cost of over 5 mills per kilowatt hour were generated in efficient plants at a coal consumption of 1.8 pounds, there is possible an annual saving of 796,000 tons of coal per year and of $6,950,000 annually in plant operation cost."[17] Conservation of coal was seen as especially important, in part because of severe shortages of coal in the winter of 1917-1918. An ability to use more efficient plants would have helped to alleviate the shortage.

The report assessed the progress that had been made, during the one year in which the military had been involved. "To sum up, it may be said that the installation of a priority program for power service, the establishment of a schedule for repairing deteriorated generators, the enforcing of more helpful relations between conflicting interests, the furnishing of important assistance in securing coal during times of stringency, and the initiation of work under the comprehensive plan for interconnection and new construction represent the full extent of progress made in remedying power difficulties in this district.."[18]

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[16] Keller, p. 12.
[17] Keller, p. 135. Here he also reports some average coal prices that indicate the extent to which prices had increased in the prior year, consistent with those reported in Section II.
[18] Keller, p. 14.

The national, state, and Pittsburgh evidence presented above is consistent with utility investment in own-system capacity, and that neither utilities nor regulators chose interconnection investment over own-system capacity. The national and state level capacity utilization estimates mask the fact that in 1916 and 1917 some resources were under-utilized and some customers were curtailed involuntarily, suggesting a mismatch of supply and demand that interconnection could have beneficially (and potentially profitably) mitigated.

V. Interpretation and analysis

Geographically contiguous utilities evaluated the choice between interconnecting with a neighboring system and investing in increasing their own capacity through investment and/or acquisition interconnection. As transmission technologies improved in the early 20th century, the associated performance improvement would have shifted the margin at which utilities decided against interconnection, leading to more interconnection as the technology improved; transmission performance improvements would have enabled utilities to absorb the transaction costs. State utility regulation changes the incentives facing utilities, making internal capacity investments the most attractive alternative to an individual utility, even when contractual interconnection would enable a higher level of reliability at the same cost or a lower cost of achieving a given level of reliability.

WWI shifted the focus to national system objectives rather than local system objectives. By having Army engineers focus on optimization of regional systems and communication across utility boundaries, the intervention of the War Department temporarily drove down transaction costs. Keller's report highlighted the many governmental and nongovernmental barriers to regional optimization:

> There is probably no other branch of industry in which duplication and division of operating control, necessary to secure competition, works for greater waste and inefficiency than in electric service where economy and reliability are best secured by interconnection and centralization. Under existing laws the comprehensive plans for development set forth in these reports would be almost impossible of execution. There is no Government agency or department empowered to carry on such work; the development of water powers by private capital on Government lands or navigable streams is restricted by conditions that are not workable; special congressional action is necessary to obtain permits for the sale or rental of water for generating power at dams created for river improvement or flood regulation; other laws, both Federal and State, are

> designed to prohibit monopolistic combinations between manufacturers producing power, thus retarding centralization and unification of generating systems; certain State laws fail to give the necessary right of eminent domain for condemning transmission line rights of way, intrastate and interstate, essential for interconnecting power systems; in most States the regulation of public utility electric business is in the hands of State commissions, which commissions differ in their policies regarding capital issues for public utility electric companies and earnings allowed, and there is no established plan for the regulation of interstate power business. … The existing [state] commissions … generally fail to work to a constructive program for unification of systems and centralization of power-generating resources to secure maximum economy for the large districts forming the most economical area for supplying power wholesale. The trouble in this respect is twofold; State jurisdiction is not broad enough for interstate undertakings, and the commissions themselves either do not 'have wide authority or do not take a broad view of interstate opportunities.[19]

The narrative and data explored above suggest that transaction costs and coordination were two economic aspects of the evolution of distribution system interconnection and the role of World War I in that evolution. In deciding whether to interconnect through acquisition or contract, utilities made make-or-buy decisions with meaningful organizational implications. Electric distribution systems began as local systems. Over time economies of scale and scope increased the size and geographic footprint of those firms and systems, yet they remained standalone, self-contained infrastructure systems. Regulation introduced legal entry barriers in a geographic service territory and entrenched the utility focus on capital investment within the service territory to meet the regulatory obligation to serve. In doing so regulatory institutions created transaction costs between utilities that reduced their incentives and abilities to interconnect, especially interstate, either for commercial or for emergency purposes. World War I temporarily reduced the transactions costs to interconnection, but the short time frame meant only a subset of the potential gains were realized. Although there was awareness in the 1920s that optimal systems would involve large new plants and regional interconnection, state regulation and state opposition to federal regulation largely limited realization of the possible gains. The onset of World War II again temporarily reduced transaction costs, but the tension between state regulation and the ability of large regional systems to deliver lower costs and higher reliability remained strong.

[19] Keller, pp. 23-24.

VI. Conclusion

We have examined the evolution of electric power systems from their earliest days in the 1880s through World War I and the economic barriers to achieving interconnection across distribution systems. In the very earliest days of electricity, gains to interconnected systems did not exist. Economies of scale were achieved at relatively low levels of output, and transmission technology was too limited to support interconnection over long distances. Indeed, initially there was often local competition. Over time, competitors tended to consolidate through mergers and acquisitions, leading to a single local monopoly. Given the high fixed costs, low marginal costs, and local monopolies, pricing, particularly retail pricing, was a concern. The policy response was municipal regulation and then state regulation through public utility commissions.

Beginning in the 1910s, interconnected distribution systems could have offered lower cost and higher reliability, and the technology systems existed to deliver those values. Utilities valuing operational control and competing in a market for industry location had little incentive to interconnect to reap reliability benefits, and would choose instead to increase their own system's capacity. Public utility regulation aligned with and reinforced that incentive. In some locations, such as the western New York-western Pennsylvania-eastern Ohio region, such economically and operationally beneficial interconnection would have crossed state jurisdiction boundaries. Utility regulation mitigated incentives for integration by allowing utilities to charge high retail prices and maintain large amounts of excess capacity to ensure reliability. Coordination costs related to building and maintaining transmission capacity and buying and selling electricity would have been significant. Further, linkages with utilities in other states may have been especially costly, if state public utility commissions had different views on regulation. As a result, interconnection, particularly involving firms in different states, appears to have been uncommon.

This preliminary analysis of the early development of electricity distribution systems suggests that self-contained utilities had little incentive to interconnect, and that regulatory institutions introduced transaction costs that prevented interconnection even once technological change made it feasible and a potentially profitable way to increase capacity utilization. By stipulating legal entry barriers, a geographic service territory, and the regulatory compact, regulation created transaction costs that reduced incentives and ability to interconnect.

Today, electric systems operate as large interconnected systems, with interconnection and contracts for bulk power starting to emerge slowly in the 1920s and 1930s.[20] One benefit of interconnecting urban distribution systems into larger networks was the ability of utilities to enter into contracts with each other for emergency power supply in case of an unanticipated generation outage or excess demand, and new transmission technologies made such contracts physically and economically feasible. The production changes resulting from World War I revealed those benefits and the limits of the existing self-contained city-based systems. The War Industries Board analyses and directives to increase interconnection in the Pittsburgh area and elsewhere provided coordination to overcome those regulation-induced transaction costs.

[20] See Neufeld (2016) for a discussion of the failed Giant Power and Superpower integrated systems proposals in the 1920s. The process of one-by-one distribution system interconnection for emergency purposes in the mid-Atlantic states formed what now operates as PJM Interconnection, one of the largest regional transmission organizations in the US.

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