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Supplementary Information for

Energy Transitions in U.S. History, 1800–2019

Robert Suits,[1] Nathan Matteson,[2] and Elisabeth Moyer[3]

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University of Chicago

Affiliations: [1]University of Chicago, Department of History
[2]DePaul University, College of Computing and Digital Media;
[3]University of Chicago, Department of the Geophysical Sciences

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Center for Robust Decision-making on Climate and Energy Policy
University of Chicago
5734 South Ellis Ave.
Chicago, IL 60637
Email: rdcep-info@uchicago.edu

Contact:

rdcep-info@uchicago.edu
Robert Suits: rsuits@uchicago.edu
Elisabeth Moyer: moyer@uchicago.edu

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Contents

1. Introduction and Overview

1.1. Overview and Approach. This document details our historical study of sectoral energy use and transitions in the United States between 1800 and 2019. We highlight the key findings from this data, describe the key sources, describe estimates for each individual fuel stream in detail, and show validation exercises. The dataset is displayed as an animated Sankey diagram at a companion website, http://us.sankey.rdcep.org/.

The United States provides a unique test case for examining energy transitions: relatively early detailed national economic records and a relatively late wood to coal transition mean that we can explore the historical dynamics of energy transitions in detail. Previous studies have estimated historical U.S. energy use by fuel type, allowing understanding of the contribution of different fuels to the energy economy, but studies do not typically evaluate what these fuels have been used *for*. Energy use by sector is compiled by the Energy Information Administration (EIA) for years after 1949, but no studies catalog sectoral use in earlier periods. This omission prevents distinguishing between, for example, coal burnt in home stoves in the 1800s, in factories and locomotives in the early 1900s, or in power plants for electricity generation in the 2000s.

Our goal is to provide a systematic assessment of the evolution of U.S. energy use by sector from 1800 to the present, merging data from different sources with minimal bias. We divide the economy into four sectors: 1) industrial (manufacturing and processing), 2) transportation (between sites rather than on-site), 3) agricultural (on-field), and 4) residential/commercial (domestic spaces and places for the exchange of goods and services). We also make a preliminary attempt at disaggregating historical residential and commercial use prior to 1949. (The EIA provides post-1949 disaggregation.) Sectors are defined in detail in Section **??** and the residential / commercial split is described in Section 3.1.1. In tracking sectoral energy use, we assign each sector its share of electricity waste heat, to correctly reflect its contribution to national primary energy use.

We catalogue primary energy inputs: biomass (fuelwood, biological oils and alcohols, and feed for draft animals), the fossil fuels (coal, petroleum, and natural gas), other heat sources (nuclear fission, geothermal), and wind, solar, and hydropower. We also catalogue these fuels' transformation into electricity. We do not count human labor, for reasons detailed in Section 5.1. For consistency in definition of primary energy inputs, draft animals are counted by their feed input, and nuclear and geothermal electricity by their heat input, i.e. we divide their output of electric power by the assumed efficiency of their turbogenerators. While many other Sankey studies assign non-thermal electricity (by hydro, wind, or solar) a similar efficiency to thermal generation, this practice makes no sense for deep historical studies since the contribution of renewables would then vary arbitrarily with the evolution of engines and turbines. In this work we therefore book-keep hydro, wind, and solar as having efficiency 1. This choice understates the relative contribution of renewables to electricity generation when shown as primary energy, but when computing fuel shares for the electrical sector, we book-keep their respective contribution to electricity production.

Wherever possible, we base estimates on primary sources: information produced by someone contemporary to the historical period in question. The chief primary sources for the pre-1949 period are U.S. government reports, especially the Census, which began in 1790 and gradually evolved into a more complete statistical record. These values are often decadal or semi-decadal. For the post-1949 period we mostly draw on the data of the U.S Energy Information Agency (EIA). Other primary sources include contemporary books, and periodicals. When primary sources are absent we turn to secondary sources – assessments by other historians, generally specialists in a given fuel or sector – or we construct energy use estimates by scaling to some proxy. For example, the inputs for horse-powered labor on farms are derived by multiplying the number of U.S. farm horses by an estimated feed per horse, and industrial energy for brickmaking is estimated using a scaling factor of 18 MJ/brick.This approach allows us to sectoral estimates at roughly 10-year intervals from 1800—1949 (generally then scaled to annual production), and annually thereafter. All inputs and outputs are converted to standard units of Watts; see Section 6.2 for physical assumptions used. We generally report in per capita units (as W/cap.), to isolate structural trends from simple population growth. (The U.S. population grew by more than ×60 from 1800–2019.)[1] Table S1 lists the seven most important sources used for deriving values and for cross-checking. Others are discussed in Section 7, which describes estimates in detail.

Table S1. The 7 major sources for this project, in order of importance. (A total of over 70 sources were used in some way, see Section 7 for details). Sources like the decennial census that published multiple reports across the years are listed here as a single entry.

Source	Type	Year(s)
1. *Decennial Census of the United States.* (1)	Primary	1800-2010
2. Energy Information Administration Annual Data (2)	Primary	1949-2020
3. *USDA Agricultural Census.* (3)	Primary	1850-2020
4. *Statistical Abstract of the United States.* (4)	Primary	1878-2020
5. Schurr and Netschert, *Energy in the American Economy, 1850-1975.* (5)	Secondary	1960
6. *Historical Statistics of the United States.* (6)	Secondary	2020
7. Lawrence Livermore National Laboratory, "Energy Flow Charts" (7, 8)	Secondary	1950-2020

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[1] This time period also saw the geographic expansion of the United States from the Atlantic seaboard to its present size. Our estimates for each time period cover the states, territories, commonwealths, and other possessions that are effectively controlled by the U.S. in each year. Estimates exclude lands and peoples that are claimed but not governed (e.g the early Louisiana Purchase and parts of the Mountain West, and early indigenous reservations).

1.2. Summary of Results. While a the main manuscript contains our primary results, we briefly outline here the primary features of U.S. energy history and major findings of this research.

Absolute energy use. As is well known, total U.S. energy usage grew steeply between 1800 and 2019, by ×180 (Figure S1a), though growth has essentially stalled since ∼2000. During this period the fuel makeup of the U.S. energy system also changed substantially. After a long period of near-complete dominance by biomass, Americans introduced first coal, then petroleum, natural gas, and nuclear-powered electricity to their homes, workplaces, and transit. On an absolute scale, this process was largely but not completely additive, In recent years (post 2005), for example, natural gas has been substituting for coal in electricity generation.

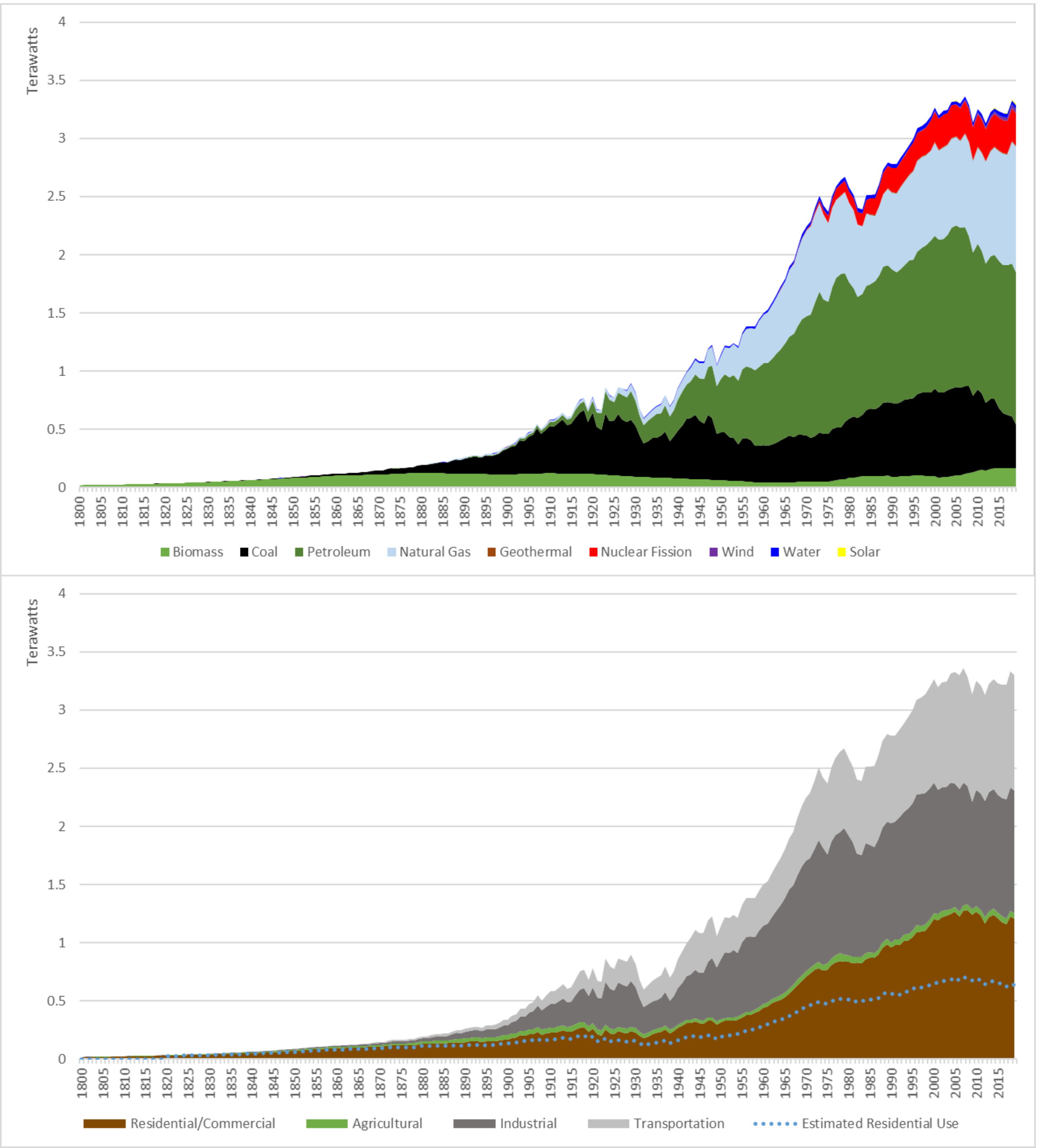

Fig. S1. Evolution of the U.S. energy economy from 1800–2019, in absolute units (TW) *Top:* evolution of energy sources across all sectors, and *bottom:* evolution of sectoral energy use, dividing usage into residential/commercial (blue), agricultural (green), industrial (gray), and transportation (red). The split between residential and commercial is marked as a dotted line (pale blue); it is estimated between 1820 and 1949, and known from primary sources from 1949 onward. See Section 3.1.1 for further details.

On the sectoral level, (Figure S1b), the energy system also shifted dramatically. Throughout the 19th century, energy use in the U.S. occurred primarily in households and farms. Only in 1901 were residential and agricultural usage outweighed by other sectors. In 2019, U.S. energy use is roughly evenly divided between industrial, transportation, and residential/commercial sectors, with on-field agriculture making a nearly negligible contribution.

Per capita energy use.. Trends in both fuel composition and sectoral energy use are better seen and understood on a per capita basis (Figure S2), since the steep rise in total energy use seen in Figure S1) is driven largely by population growth. Per capita U.S. energy use grew only ×3 from 1800–2019 (Figure S2a). This relatively modest scale of increase reflects anomalously large residential energy use in the early U.S., relative to that in contemporary European states. In 1800, for example, U.S. household energy use is ∼2850 W/cap. versus *total* per capita energy use of ∼560 W/cap. in Netherlands and ∼490 W/cap. in France (9). Early U.S. energy use is nearly double even the highest energy users in contemporaneous Europe: England at ∼1500 W/cap. (10) and Sweden at ∼1400 W/cap. (11). The problems with Colonial American household heating are extensively documented in contemporary letters, which describe inefficient open fireplaces and vast consumption of wood (12, 13). The per capita perspective also makes clear the profound adjustments that followed energy crises in the 1910s (coal) and 1970s (oil and gas).

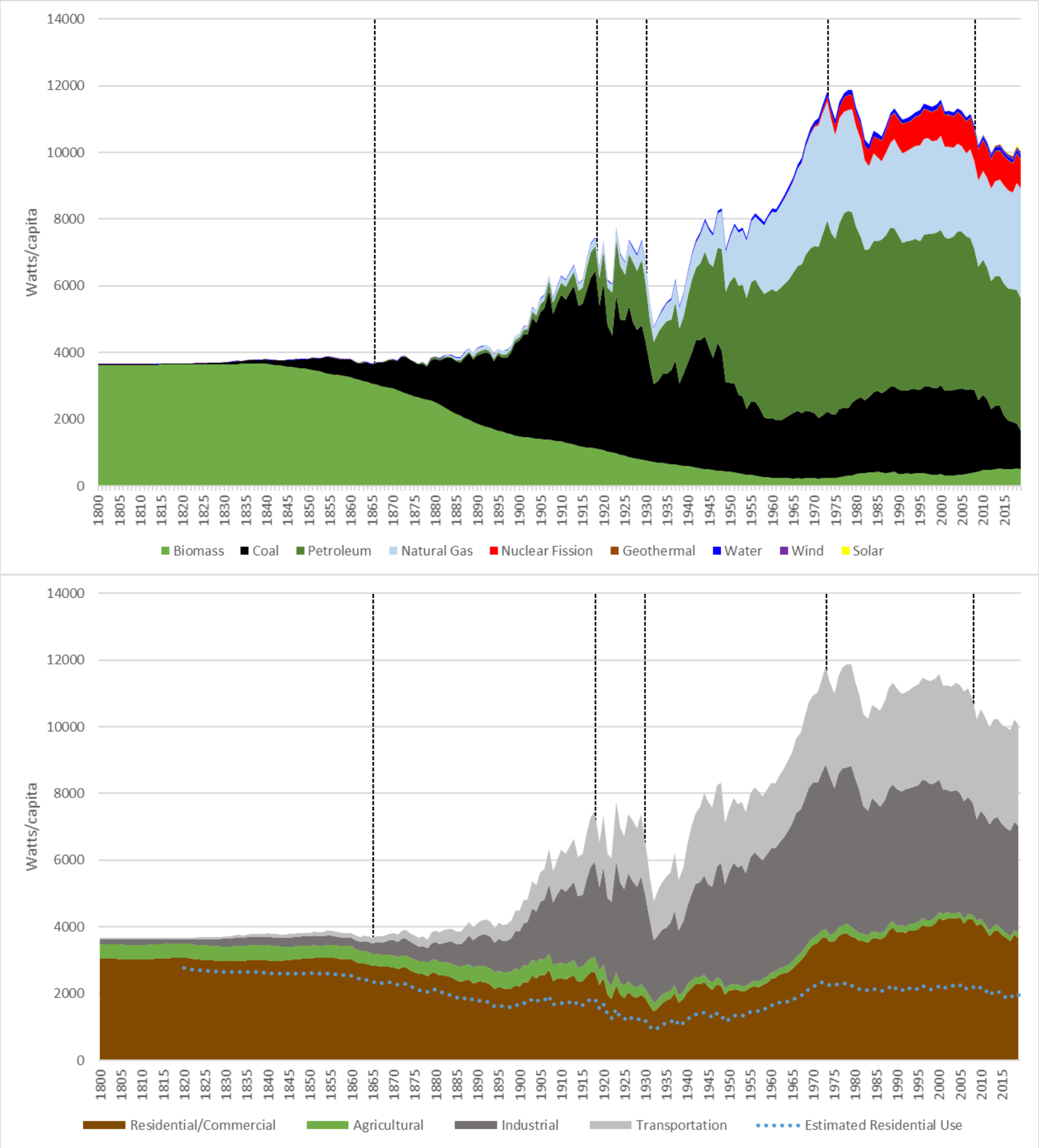

Fig. S2. Evolution of the U.S. energy economy from 1800–2019, as in Figure S1 but now in per capita units (W/cap.), to removes the effects of population growth that dominate Figure S1. Dashed vertical lines mark historical events associated with changes in energy use: the end of the Civil War (1865), a period of labor troubles and price increases in coal, especially during and after WWI (1918), the stock market crash that set off the Great Depression (1929), the OPEC energy crisis (1973), and the Great Recession (2008). Note that variability of coal use in the 1910s may be exaggerated due to the exclusion of coal stocks; see 7.1. The 1979 drop in petroleum and natural gas is associated with the Iranian revolution.

Residential energy use is unique among U.S. sectors in showing a U-shaped evolution, from the initial high usage of the early 1800s, to a 3-fold decline between 1860 and 1935, followed by several decades of growth, so that current U.S. household energy use again nearly matches that of two hundred years ago. The drop that began in the 1860s is associated with a transition from wood to coal, and reflects the replacement of inefficient open fireplaces with more fuel-efficient stoves (13).

By contrast, energy use in sectors other than residential and agricultural grew enormously from 1800–2019: industry by ×250; transportation by ×70; and commercial (estimated only, see Section 3.1.1) by a more modest but still substantial ×6 (Figure S2b). The per capita representation more clearly shows several major historical shocks that interrupted this growth, including the Great Depression of the 1930s, the OPEC oil crisis of 1973, and the Great Recession of 2008–2009. After the 1973 OPEC crisis, per capita energy usage in the U.S. transportation sector leveled off, while that in industry actually contracted, largely because of manufacturing moving offshore (14–16). After about 2003, an additional sharp decline in primary energy use is seen in both industrial and residential/commercial sectors; this is a side-effect of the fracking revolution, which lowered the energy costs of electricity generation as cheap and efficient natural gas has increasingly replaced coal.

Agriculture is the only U.S. sector to show a net decline in per capita energy use over time. On-field farm energy use remained relatively steady for over a century until roughly the 1920s, when it dropped by over half as tractors replaced horses. While "bio-engines" and the internal combustion engines in tractors are comparable in their efficiency of converting fuel to mechanical work (17, 18), tractors, unlike horses, can be turned off and do not consume fuel when not working. Note that this book-keeping does not include the energy costs for manufacturing industrial fertilizer, which are considered a part of the industrial sector. Adding in the embodied energy of fertilizer, which began to be widely used after World War II, still leaves modern agricultural energy use at half its Colonial equivalent. (On-field use was 430 W/cap. in 1800, and in 2019 is 150 W/cap. on-field + 65 W/cap. fertilizer, for a total of 215 W/cap.) See Section 3.2 for details.

Insights into energy transitions / further results. Examining energy use in individual sectors provides insights into the factors governing energy transitions. Figures S1–S2 make it clear that the wood to coal transition both allowed a tremendous expansion of U.S. energy use, and was coincident with major structural changes in the economy. In the early 1800s, the U.S. economy overwhelmingly relied on flows of energy that passed from the sun through living things (sometimes called the "organic economy" (19), or the "animate economy" (20)). Heat was derived from fuelwood, and motive power from muscles, largely from horses, which provided the bulk of power for overland transport and agriculture. Wind and waterpower served important functions – for sailing ships, which provided transport over water, and mills, which processed grain into flour or cotton into fabric – but their contribution to total energy use was small. The growth of the transportation and industrial sectors required the additional energy sources provided by fossil fuels.

The sectoral perspective also shows that not only did individual end uses sometimes see a change in fuels, but individual fuels sometimes underwent complete changes in use. For example, coal dominated every single sector other than agriculture in 1918; by the 1950s, coal was almost entirely replaced in the transportation and residential sectors by petroleum and natural gas, and it was used overwhelmingly for generating electricity (manuscript Figure 4). The transition was driven not by price but by the convenience of the expensive but more easily transported and cleaner-burning new fuels. Coal survived extirpation only because electricity provided a new niche where its deficits mattered less and its low cost provided an advantage (21, 22).

Examining individual sectors allows understanding constraints on the speed of energy transitions. Manuscript Figure 5, which shows the evolving shares of different fuels in each sector, demonstrates that a transition in an individual sector could could occur very quickly, in a decade or less, if it occurred relatively late, after distribution systems for a new fuel had already been built out. Industrial use of coal, for example, was facilitated by earlier residential use and the associated construction of the railroad network. In the 1940s–50s, households could quickly switch to oil heating and farms could quickly adopt gasoline-powered tractors only because infrastructure for petroleum extraction, processing, and distribution had been in development for nearly a century.

Sectoral breakdowns provide extensive insight into individual transitions, beyond what could be covered in the main manuscript. Section 3 shows the detailed evolution of individual sectors, repeating a version of Figure S2 for each sector. These show that transitions in fuel share within a sector were often also associated with changes in per capita fuel use. In some cases, new technologies required less energy for a given function: for example, the replacement of open fireplaces with efficient coal-burning stoves, or the replacement of horses with tractors. In other cases, new technologies enabled new functions and led to greater energy demand. For example, the rebound in residential / commercial energy use in the 1960s was driven not by heating but by rising use of electricity for new purposes, appliances and air-conditioning (Figure S5). The rebound in on-field agricultural energy use was driven by adoption of energy-intensive indoor animal husbandry (Section 3.2, with Figure S7 adding the implicit energy in industrial fertilizer). In many cases, changes in fuel choices or energy use involved more complex drivers. In U.S. industry, the shift away from mining and metallurgy and toward chemicals and refining drove a long-term decline in coal and increased use of natural gas and petroleum liquids (Section 3.3). In transportation, the labor unrest of the 1910s led to a precipitous drop in per capita coal usage in railroads and marked the beginning of the eradication of coal from the sector (Section 3.4).

Additional results include: in Section 3.5, we back out the evolving efficiency of thermal generation over time, from 2.5% in the first commercial electricity production to 30% by the 1960s to over 40% in 2019 with the increased use of natural gas-combined cycle plants. In Section 4, We compare the evolution of the energy intensity of the U.S. economy to that of other countries, and show that the concept is more salient if residential energy is excluded. Finally, in Section 5, we discuss two energy sources omitted from this dataset – the energy flows associated with use of natural ice for refrigeration, and with human labor – and show that both are relatively small. We estimate that natural ice is <10 W/cap. at peak use, and the energy output of human labor is substantially below that of draft animals (horses, oxen, and mules).

2. Overview of Sources

In this section, we give an overview of the source base for the various time periods covered by this study and describe three of the most important sources in detail. Section 7 provides extensive details on how each individual energy flow is estimated.

As a general rule, energy sources that are centrally extracted (e.g. coal, petroleum, and natural gas) are better tracked than those harnessed in a more distributed or diffuse way (biofuels, water, wind). Use statistics are also poorly collected for energy sources that are rarely bought and sold, e.g. fuelwood, hay or other horse feed, early wind and water power. Data collection on any given historical energy source has often only begun after it had already become a significant part of the U.S. energy economy. For example, electricity production appears in primary government statistical records only in 1912, thirty years after the first commercial electricity sales. The timeseries for each energy source is therefore least certain near its initial adoption. The exceptions are those fuels that were widely seen as the fuel of the future, regardless of their actual importance. Nuclear fission and ethanol were both closely tracked throughout their period of use.

2.1. Sources by Period.

We distinguish four periods of energy data in United States history: pre-1850, the 1850s–1890s, the 1900s–1949, and 1949 to the present.

Before 1850, the data-collection apparatus of the U.S. government was limited. While the U.S. Census was constitutionally mandated, and its decennial count inaugurated in 1790, the questions asked by Census officials were narrow in scope. The 1790 Census, for example, asked simply how many persons of the following categories were present in each household: free white men above 16 years in age, those below 16; free white women; the number of other free persons; and the number of slaves. In the 1810 Census, the Bureau tracked the production of industrial goods through a survey of manufacturers, but the process was not repeated again until 1840. Census enumeration of topics such as fuel use by industry did not begin until the 1890s (1). While prior research has produced some aggregate statistics – for example, how many square miles of forests were lost, or how much coal was mined across the country – breakdowns by sectoral use often require use of proxies.

We estimated the sectoral breakdown of wood and coal and the use of waterpower in industry by using specific commodities as indices for each sector. For the fuels burnt for heat, wood and coal, we estimate use in industry based on the production of iron and steel, brick, glass, and cement, and use in transportation based on well-reported figures like the tonnage of steamships and railroad activity. Once industry and transportation are accounted for, the remainder of wood and coal —- the bulk of the energy use – must be in the household (and the tiny commercial sector). The resulting residential inferences are consistent with studies that aggregate primary source estimates of e.g. wood burnt by the average person. Waterpower is more problematic, since water mills were largely undocumented at the time and are studied in the secondary literature only for the 1850s onward. We estimate water power based on textile production.

The use of draft animals and sailing ships are better documented. The ratio of draft animals to humans is well established, and the *Historical Statistics of the United States* provides a complete count of sailing vessel tonnage throughout U.S. history. Given reasonable physical assumptions, these values can be converted to primary power estimates.

1850–1890. The second half of the nineteenth century saw rapidly expanding interest in and reach of the American government's statistical capabilities, a part and parcel of the expanding United States federal government during and after the Civil War (23, 24). The executive branch regularly compiled reports on selected industries, and the United States Census rapidly scaled up in detail. After 1850, for example, the number of horses used in agriculture became regularly tracked; several contemporary estimates for aggregate sectoral demand for fuel wood became available; and industrial power was directly reported, both in the decennial Census and in various Statistical Abstracts that compiled data collected by the Departments of Agriculture, Labor, and the Interior. Federal departments paid observers at the county level to produce various estimates annually, such as the percentage of each county's wheat acreage that was harvested (3).

In this period, Americans – and Europeans – increasingly became concerned about depletion of natural resources (25, 26). It also became common to view economic activity as some form of energy transformation, a view that still informs our understanding of the energy economy (27). These trends led government officials to track fuels specifically as sources of energy, rather than only as any of a number of commodities and resources.

This period saw the introduction of new fuels like petroleum and natural gas, and the beginnings of the electric sector. The first oil well was drilled in 1859, natural gas effectively dates to the 1880s, and the first commercial electricity sales occurred in 1882. Estimates of oil and gas production were recorded from their inception, but records of individual refined products begin only later: kerosene and gasoline from 1875, fuel oil from 1880, and diesel and many other refined products not until 1935. Assigning petroleum in this period to individual sectors is therefore complicated. We estimate production of refined products and their specific uses through a variety of proxies. In many cases we hold sectoral shares constant at their earliest recorded values in the early 1900s. Exceptions are those cases where we know when a specific fuel use began, e.g. the use of gasoline in transportation, which did not happen before the automobile in 1890s; see Section 7.11). In the earliest years of oil and gas development, much of the production of individual wells was lost before being captured and therefore not tracked. Of crude oil retrieved, about 20% of its energy content was discarded after refining, because the primary saleable refined product was kerosene for household lighting (28, 29). We assign this wastage to industry, treating it as part of refinery operations.

The early use of electricity is poorly tracked. Most electrical generation was generated for private or municipal use and leaves no record of sales to customers. For example, individual towns sometimes generated power using a single steam turbine or water dam (30). Although the first commercial electricity came in 1882 (Edison's coal-driven Pearl Street generating station in Manhattan and a hydropower plant in Wisconsin), even commercial electricity has reliable statistics only from 1902 onward (compiled by the Edison Electric Institute). We use reports in the early trade periodical *Electrical World* to construct a coarse estimate of sectoral demand for electrical power, the bulk of which went to lighting, powering electrical railways, or electrical motors in factories. It is likely that more complete estimates could be constructed with research on the archives of power companies, who kept records of sales to individual consumers.

1900–1949. In the first half of the twentieth century, the federal government continued to expand in size, power, and record-keeping reach, both before and particularly after the establishment of the New Deal state in the 1930s. By the 1930s, energy statistics were collected by a variety of officials in the Bureau of Mines and the Department of Commerce. Everything from the amount of petroleum purchased by farmers nationwide to the aggregate delivery of coal to households could usually be found in one abstract or another; only a few industries (such as railroads) remained somewhat secretive about their operating costs and revenues. However, agriculture was not tracked separately and our estimates of agricultural fuel use in this period depend on historical reconstructions of the number of tractors in the U.S.

Several forms of energy use, including distributed and household generation of electricity, remain difficult to estimate. Rural consumers sometimes generated electricity decades before their towns were fully electrified, through small wind turbines or even wood-burning engines (31); these constituted less than two tenths of a percent of electricity use before 1949. Private rural electricity generation is systematically documented only from the 1960s on. For completeness, we have tried to estimate these figures where possible.

1949-present. Data collection is widespread from 1949 onwards. Many different sources corroborate each other on the breakdown of energy sources and uses, and the Energy Information Administration (EIA) has tallied detailed energy use statistics, broken into each of our sectors except agriculture. From 1949 onward, virtually all of our data is sourced from the EIA. Only a few small parts of total energy use remain systematically underexplored in government datasets, such as the continuing use of wind pumps in Great Plains agriculture. Agricultural use is not tracked separately by the EIA but can be more reliably estimated; we subtract agricultural energy use from the EIA "industry" total.

Several new primary energy sources came into use during this period, all used for electricity generation: nuclear, solar photovolatic and thermal, and geothermal. (A small portion of geothermal energy was also used directly for home heating.) All of these sources have been thoroughly documented from their emergence to the present, other than small-scale (e.g. residential rooftoop) solar PV, which the EIA estimates only from 1990.

During this period, the Lawrence Livermore National Laboratory (LLNL) has produced a semi-independent estimate of energy use by fuel and by sector that we use for validation purposes only. LLNL Energy Flow Charts are available in a variety of agency reports for 1950, 1960, 1970, 1976, and 1978 (8) and annually thereafter for all years except 1993 (7).

2.2. Details on Selected Sources.

This section covers various major sources in this project, including their extents, utilities, and limitations.

Government Statistical Collection. The central primary source for this project is the United States Census, which has been conducted every 10 years since 1790. While the primary goal of the Census is to provide a summation of all persons in the country, it also collected statistics on measures such as labor practices, industry, agriculture, and production and consumption of goods. These additional figures are typically provided in individual reports bundled together as part of the decennial Census – e.g. individual reports on agriculture, manufactures, etc. (See Section 3 for further detail.) Note that since the chief purposes of the U.S. Census were to aid in drawing congressional districts and later, to survey taxable assets, it provides an incomplete estimate of U.S. energy-related activities, as it does not seek to quantify informal economies such as domestic consumption of fuelwood. Some further annual figures were estimated by agents employed or recruited by the United States government, and often appear in the *Statistical Abstract of the United States.*

The Census makes study of historical energy use in the U.S. distinct from that in other countries, as few other countries have made, or indeed been able to make, such a consistent, centralized, and sustained effort to collect statistics across so many subjects, especially across an energy transition as with that from wood to coal. Even British sources cannot provide as comprehensive a picture of an energy transition as the United States, since their primary transition from fuel wood to coal occurred in the 18th century, before the centralized collection of statistics. Continental European nations might provide a useful point of comparison, but other polities, e.g. those of China or India, have had their statistical collection destroyed or interrupted by colonial and anti-colonial conflicts.

Energy Information Administration (EIA) Tables. Beginning with its founding in 1977, the Energy Information Administration (EIA) published tables of energy use based on government data collected by the Departments of Commerce and the Interior. The EIA has generated retroactive timeseries to 1949 of fine-grained detail on the production, import, export, and consumption of different energy sources in the U.S. (2), as well as more a informal estimate to 1775 that we use only for validation (32). EIA tables are the definitive reference for modern U.S. energy studies.

Schurr and Netschert, Energy in the American Economy: 1850-1975. This comprehensive work was produced by the energy studies group at Resources for the Future in 1960. Their research drew on U.S. government statistics across multiple agencies, combined with extensive primary-source research, to produce a systematic assessment of the historical use of individual energy sources between 1850 and its publication (with some outlook on the future). Schurr and Netschert remains the definitive reference for U.S. energy history.

3. Results: Fuel Use of Individual Sectors

3.1. Residential/Commercial.

3.1.1. Disaggregating the Residential and Commercial Sectors, pre-1949. EIA estimates allow us to disaggregate residential and commercial uses after 1949. We estimate commercial energy use between 1820—1949 by using employment statistics to estimate the relative importance of the commercial sector over time. That is, we scale the aggregate residential/commercial energy use by the relative number of people in businesses and households.

The Census tracks employment in various industries (1) from 1820 onwards. We aggregate all people working in sales, non-transportation-related exchange, and non-household services as "commercial." To count people working in the household, we include from the Census employment in household services and in agriculture (as farms and residences were overlapping categories for most of this period), and add to that all non-employed people (the difference between total population and total employment). We then estimate commercial energy use in each pre-1949 year i as the appropriate proportion of total residential/commercial energy:

$$E_c = E_{rc} \cdot \left(\frac{L_c}{L_{rc}}\right)_i / \left(\frac{L_c}{L_{rc}}\right)_{1949}$$

This scaling adjusts the assumed contribution of commercial energy use in proportion to its changing employment.

The results are broadly reasonable (Figure S3). In this accounting, commercial energy use, like that in industry and transportation, grew almost monotonically in per capita terms. As a fractional share of retail energy deliveries, commercial rose from about 10% in 1820 to 38% by 1950 when the EIA estimates begin (reaching 46% by 2019). The decline in energy use in the residential/commercial sector from 1800 to 1935 is attributed almost entirely to domestic usage. Much of this decline is likely caused by the switch from open hearths to more efficient forms of home heating, first coal stoves and then central air or steam heat (13), and while commercial establishments likely followed these trends, the growth in the sector would have more than outweighed them. Residential usage fell sharply in the 1910s, possibly driven by households cutting back on heating at a time of both rising coal prices and an economic slump after the First World War. The more modest decline during the Great Depression appears in both sectors.

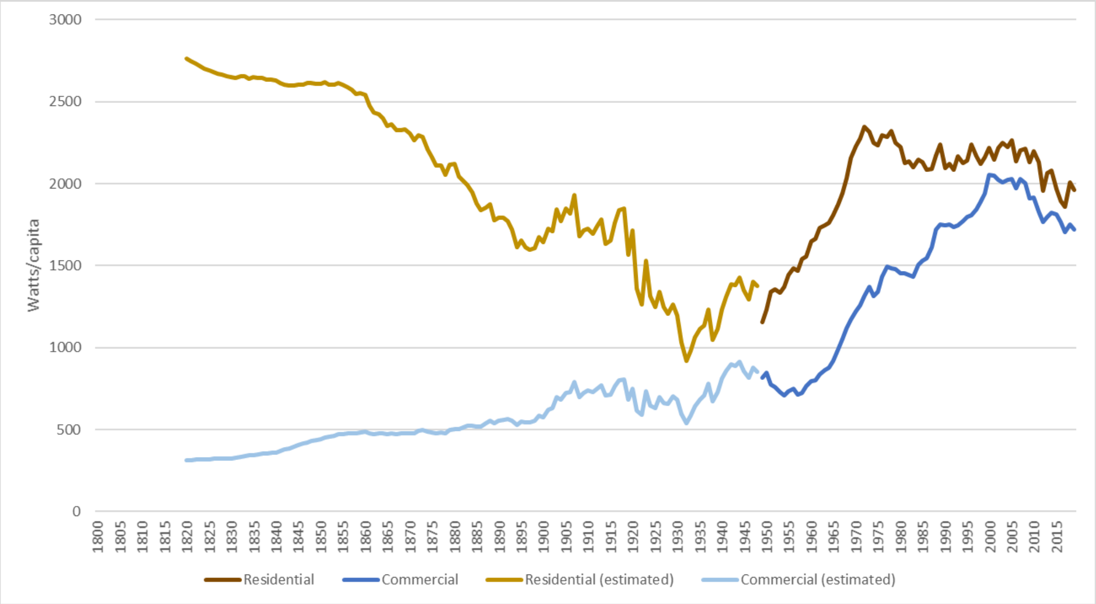

Fig. S3. Disaggregating the residential/commercial sector, 1820–2019. Energy used in residential (blue) and commercial (orange) subsectors, with paler colors indicating pre-1949 estimates derived from proxy data rather than directly reported. Pre-1949 data is extrapolated based on the growth of national employment in the commercial sector relative to the number of unemployed individuals (assumed to be working in the household) (1). Post-1949 data is reported directly by the EIA (2). The apparent discontinuity between the two datasets is a result of a more systematic discontinuity between EIA and pre-EIA data, discussed in section 7.14.

After 1949, EIA estimates show that both sectors expanded rapidly through the 1960s, in both absolute and per capita terms. The expansion involved both heating and electricity and was likely due to a combination of larger buildings and increased air conditioning use (33). After the 1973 OPEC crisis, when energy prices spiked, residential use dropped slightly while commercial use continued to climb. Energy use in both sectors declined after about 2003 because in our book-keeping, the primary energy assigned to electricity-using sectors is dependent on the efficiency of generation. This decline reflects the replacement of coal-fired electricity generation with more efficient gas.

To place residential and commercial energy use in context, we show it next to all other sectors in Figure S4. This figure makes it clear that residential use was indeed the dominant sector of the American energy economy before the twentieth century. After 1900, both transportation and industrial sectors individually surpass residential energy use. Note that the

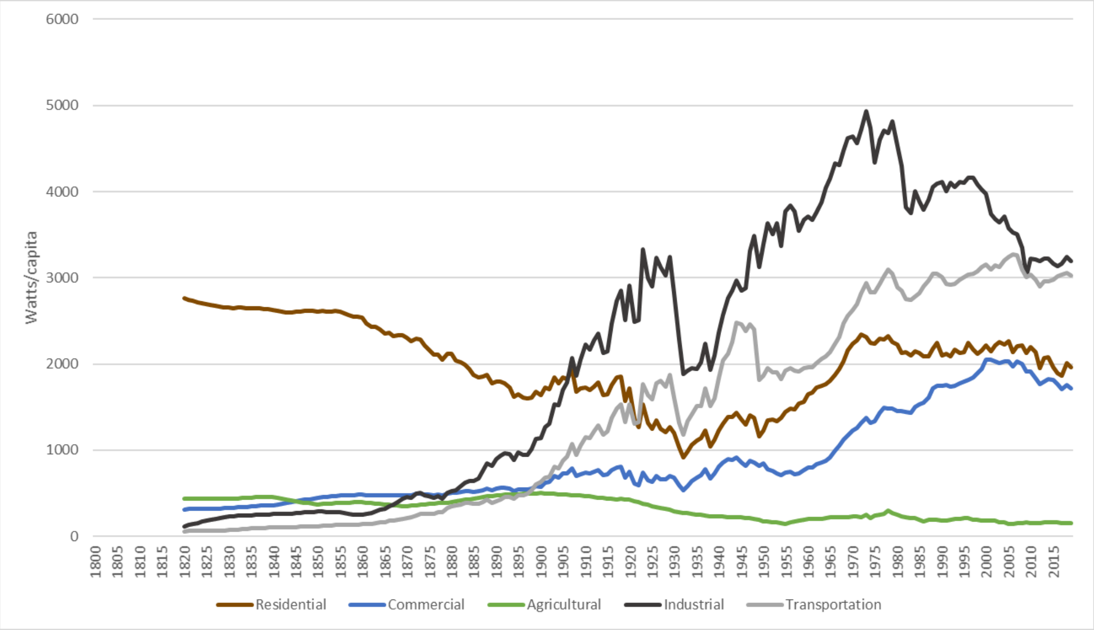

Fig. S4. The residential and commercial sectors in context, 1820–2019. Figure shows estimated values from Figure S3 in context with other sectors. The pre-Civil-War rise in commercial energy use parallels that in transportation and industrial sectors, but commercial does not show the same postwar acceleration.

post-2003 energy use decline associated with electricity generation efficiency is not apparent in transportation or industry, sectors that involve little use of electricity. On the other hand, the 1970s decline after the OPEC crisis decline is strongest in industry and transportation, sectors heavily dependent on oil.

3.1.2. Transitions within the Residential/Commercial Sector. By our definition, the residential / commercial sector experienced two energy transitions, from wood to coal (1883–1904) and from coal to a combination of oil and/or natural gas for heating, and new uses of electricity (1946–1950). Sectoral energy evolution is shown in per capita and fractional terms in Figure S5 below.

Early American residential use was extraordinarily high, as discussed previously. Early U.S. energy use was dominated by wood burned for home heating. American houses were large and inefficiently heated compared to European contemporaries (5, 13), with the combined effect that U.S. residential home heating per capita was nearly triple the total energy consumption of the average European across *all* sectors (9). (Note that virtually all non-electrical home energy use goes to heating, both in early U.S. history and more recently (8).) The biofuel category in Figure S5 includes biological fuel oils (from whales, distilled alcohols, etc.) for home lighting, but lamp fuel was a relatively minor part of energy consumption and totaled less than 1 W/cap. even at its peak.[2]

Over the course of a half-century, residential and commercial users largely abandoned fuel wood in favor of coal, with use falling in absolute as well as per capita terms. Coal made slow inroads into the residential sector as early as the 1820s–1830s, especially in urban areas (13, 29), but the bulk of this transition occurred between 1883–1904. This adoption required not only access to coal but also acquisition of stoves: in open hearths, temperatures are too low to ignite even the lowest grades of coal (29, 34). The expansion of U.S. railroads appears to have played a vital role in this transition, carrying both fuel and stoves to the rural areas that comprised the bulk of the consumer population and did not otherwise have access to eastern resources (13, 35). Drivers of the transition are still debated, but presumably involve some contribution from deforestation and urbanization that reduced access to fuelwood and raised prices. Although urban households were still a minority of the population in the late 1800s, they are seen as important leaders in the adoption of new fuels (26, 36).

From about the 1940s on, coal was replaced in family homes by newer fuels for heating and cooking, first petroleum and later natural gas. By 1960, coal made up less than 10% of residential energy use, and by 1970 less than 2%. The residential transition away from coal was rapid, only 5 years by our definition (as the period over which a dominant fuel falling between 70–30% of its peak share) in part because significant use of petroleum and natural gas had begun decades earlier in industry and transportation. Energy use for heating remained relatively constant across this transition, at roughly 1000–1500 W/cap., barring an episode of higher oil and gas use in the late 1960s–early 1970s just before the OPEC crisis. A decline from the 1980s appears driven by the diminishing importance of inefficient oil-fired heaters.

Overall residential/commercial energy use has increased since the 1930s, driven entirely by increasing use of electricity. Much of this electricity energy use involves new uses not relevant in earlier periods, e.g. home appliances and air conditioning (8). The result of this growth is that if residential and commercial are combined as in Figure S5, they are since 1999 again the single largest U.S. energy-using sector, as long as sectoral book-keeping properly includes the waste heat of electricity generation.

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[2] This minor fuel stream associated with lamp oil still had severe ecological consequences, with some whale species hunted nearly to extinction (28).

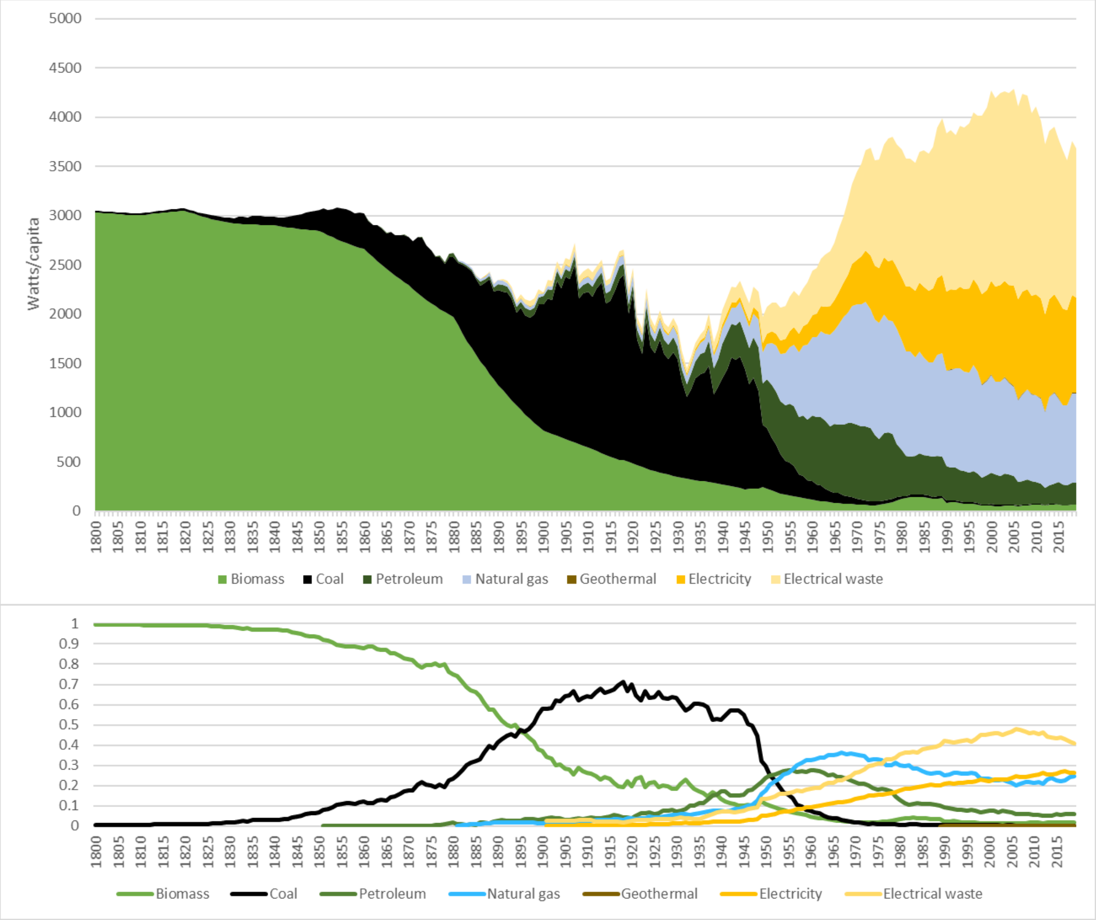

Fig. S5. Fuels used in the residential/commercial sector, as a stacked bar graph in W/cap. (top) and as fuel shares (bottom), repeating part of manuscript Figure 5. By our definition, the residential/commercial sector has undergone two periods of transition: 1883–1904 (from biomass to coal) and 1946–1950 (from coal to a mix of fuels). Both panels separately show the electricity used directly and the share of waste heat of thermal electricity generation assigned to the sector. For further details on how values for individual energy sources in these figures are derived, see Sections 7.1, 7.5, 7.7, 7.10, 7.11, 7.12, 7.13.

3.2. Agricultural. By our definition, the agricultural sector experienced two energy transitions, first from animal feed to petroleum-powered engines for motive power (1944–1955) and then an ongoing transition that reflects the evolution of the sector to include intensive indoor animal husbandry (1977–present). Agricultural energy evolution is shown in per capita and fractional terms in Figure S6 below.

Early U.S. agricultural energy consumption centered on draft animals (horses, mules, and oxen), which represented by far the largest energy use outside of the household. Before the Civil War, the >400 W/cap. feed inputs for draft animals on farms exceeded the *combined* energy usage of the U.S. transportation and industrial sectors. Agriculture was also the most valuable sector of the American economy in the nation's earliest days (6).

Draft animals remained central to U.S. agriculture a century after they had been superseded in other sectors. In transportation, energy inputs to engines (on steamboats and steam locomotives) surpassed that to horses around 1850. Because farm work required lightweight and flexible prime movers, the agricultural transition had to wait until the development of reliable, cost-effective internal combustion engines. Once the transition began, however, it could proceed quickly not only because the petroleum system was already well-established, but because the switch involved only a simple substitution of a source of motive power. Farm work was already mechanized by the end of the nineteenth century, with draft animals pulling complex seeders, mowers, and combines (37). The transition therefore proceeded in under a decade, by our definition. While draft animals consumed over 90% of farm energy in 1930, they were nearly eliminated by by the 1950s, and the U.S. government ceased counting draft animals as an agricultural input after the 1954 Agricultural Census (3).

Although modern agriculture is frequently maligned as being resource-intensive and environmentally unfriendly (38), it is important to realize that modernization actually lowered on-field energy use. A horse is powered by biofuel, but its basic metabolism must be maintained even when it is idle. Targeted breeding allowed horses to grow in size and power over the course of the nineteenth century (see Section 7.6), but breeding could not alter their fundamental inefficiency. Horses must be fed even in the winter, when they are not working; a tractor can be turned off. Per capita energy use for motive power on farms therefore dropped by half when modern equipment was adopted.

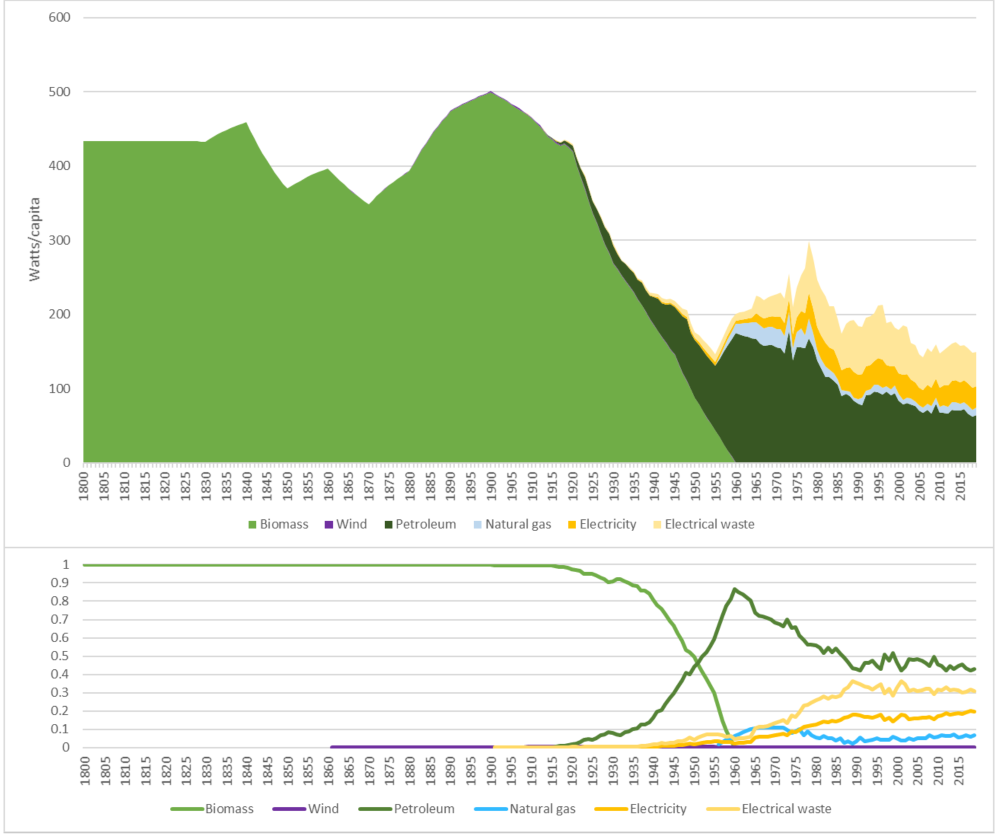

Fig. S6. Fuels used in the agricultural sector, as a stacked bar graph in W/cap. (top) and as fuel shares (bottom), repeating part of manuscript Figure 5. We count on-field use but not processing or food preparation off-site. By our definition, agriculture has undergone one energy transition: 1944–1955 (biomass to petroleum), and is currently undergoing another, 1977 to the present (petroleum to a mixture of petroleum and electricity). Note that our definition of an energy transition is problematic when the transition is to a new regime involving a mixture of fuels. The rising electricity in agriculture did not replace petroleum but instead enabled new uses (the growth of large factory farming). "Biomass" here is largely feed for draft animals. The sharp drop associated with replacement of horses by petroleum-fueled engines occurs because draft animals consume feed when on working. For further details, see Sections 7.6, 7.9, 7.11, 7.12, 7.13.

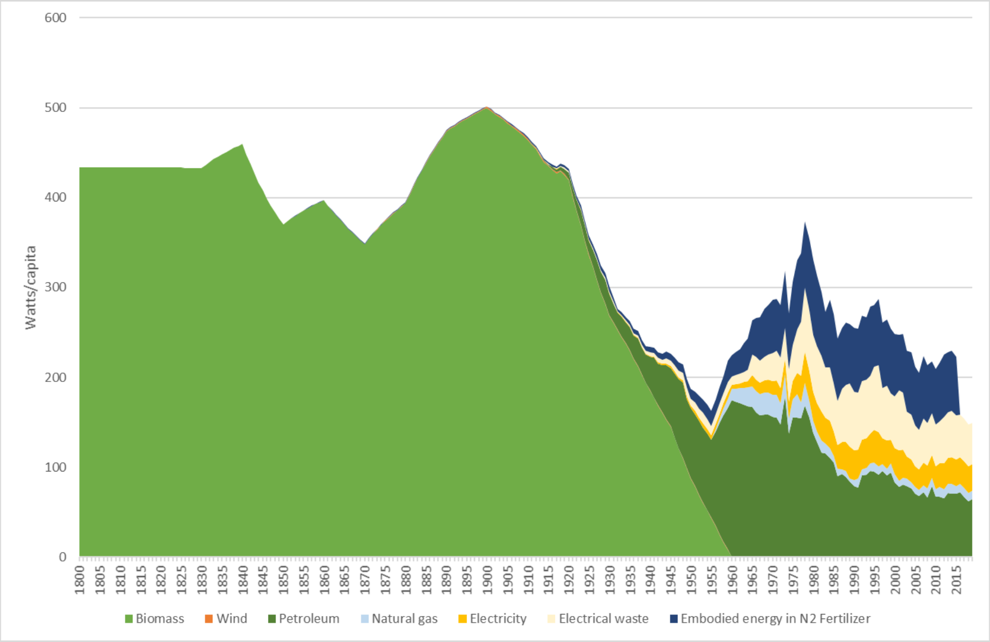

Fig. S7. As in Figure S6, top, but here including the embodied energy in nitrogenous fertilizers, using historical estimates of U.S. fertilizer use from data from (39).

Modern agriculture now involves increasingly industrialized operations and use of electricity and natural gas in climate-controlled livestock facilities (40, 41), but farm agricultural energy use remains below its 19th-century value (Figure S6). This statement holds true even when we add the endogenous energy of modern industrial nitrogenous fertilizer, whose use grew rapidly after World War II (facilitated by repurposed munitions factories) (42). In Figure S7 we add an energy input based on historical U.S. nitrogen application from (39) and an assumption of 60 MJ/kg embodied energy (mid-range in (43)), which yields ∼65 W/cap. in 2015 (the last year where Cao et al. provide data). The total is still less than half the per capita energy use of a century earlier. (We omit endogenous energy in pesticides, which is smaller than the contribution from fertilizer (44).)

Although agricultural energy use is a small part of the U.S. energy system throughout the period we survey, the higher historical farm energy use should remind us that agriculture has not been a net positive energy producer for centuries. That is, the food calories produced on a farm have long been less than the energy inputs required for their production. A human diet of 2500 Calories/day is equivalent to 120 W/cap.; that number is exceeded at all times in Figures S6–S7. Agriculture is then best thought of not as a means of harnessing solar energy for food, but as a necessary but inefficient means of converting inedible fuels (grass, petroleum, natural gas) to a form that humans can eat and enjoy.

3.3. Industrial. By our definition, the industrial sector experienced two energy transitions over the period of study, from wood and water power to coal (1851–1870), and away from coal and to increasing use of petroleum, natural gas, and electricity (1921–1947). This transition reflects a change in sectoral activities. Industrial energy evolution is shown in per capita and fractional terms in Figure S8 below.

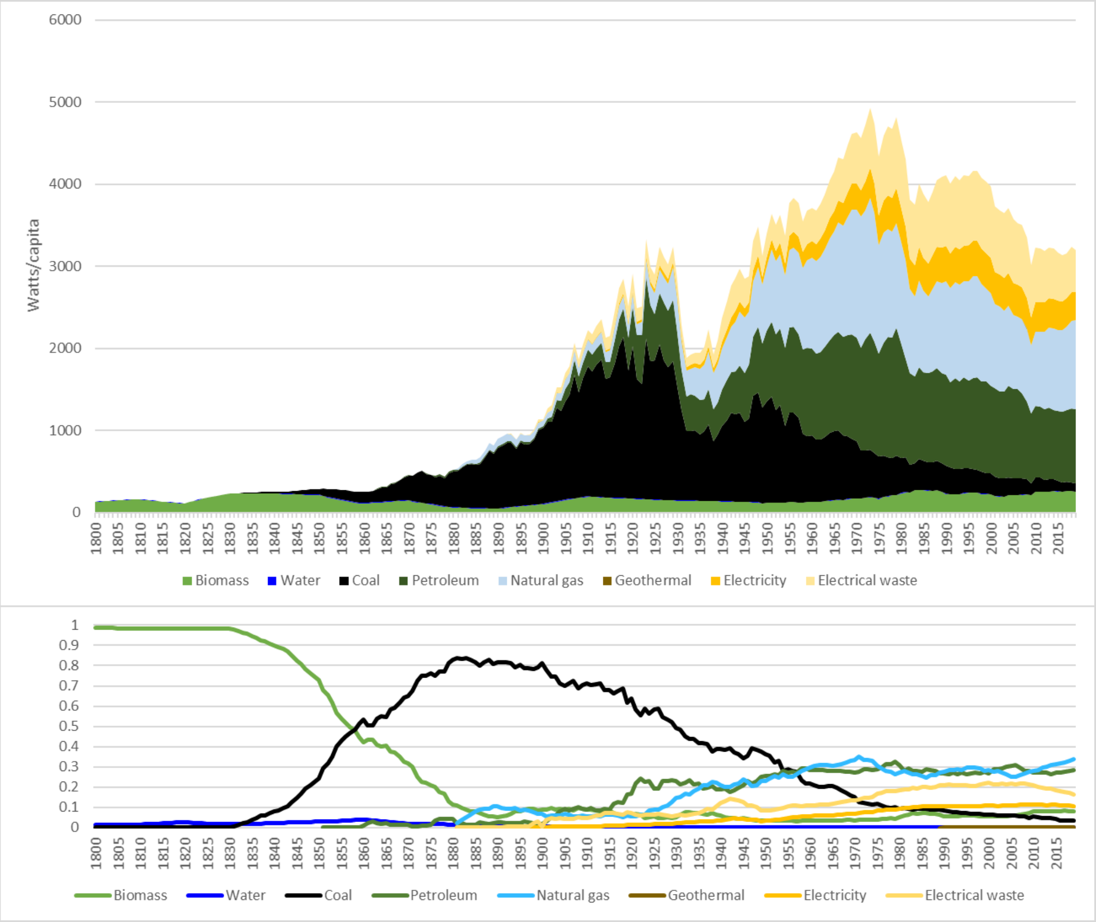

Fig. S8. Fuels used in the industrial sector, as a stacked bar graph in W/cap. (top) and as fuel shares (bottom), repeating part of manuscript Figure 5. Industrial energy use in per capita units peaked 1973–1979. By our definition, industry has undergone two periods of transition: 1851–1870 (from biomass to coal) and 1921–1947 (from coal to a mix of fuels). Long-term decline in industrial coal use is driven in part by shrinking U.S. steelmaking. Natural gas use has risen since the fracking revolution of ∼2003. For details on individual estimates, see Sections 7.1, 7.2, 7.5,7.8, 7.10, 7.11,7.12.

U.S. industry experienced radical growth over the period under study. In 1800, industrial operations barely existed in the United States. The processes that dominate industrial energy at later dates – chemicals and refining; glass, cement, and paper – were limited or nonexistent in 1800. Early industrial use largely involved burning coal and charcoal for heat for smelting iron from ore and transforming it into finished goods (29), with virtually all of this energy from charcoal (see Note 7.2).

Industrial energy use in the U.S. has been dominated by process heat and, in the 20th century, by use of hydrocarbons as feedstocks. Motive power (mechanical work) has always made up a relatively small percentage: less than 2% in 1800; likely between 16–40% in 1900;[3]; and about 20% in the 1990s.[4] For this reason, even complete substitutions in the energy sources for motive power in manufacturing will not produce a sectoral transition.

In the early 1800s, U.S. manufacturing relied primarily on water power for nonhuman mechanical work.The New England had many suitable rivers, and water wheels were more convenient than animal power and cheaper than imported steam engines. Domestic manufacturing capabilities were limited. Only three stationary steam engines were installed in the U.S. before the American Revolution, to pump out mines, and pumping engines were installed for municipal waterworks in Philadelphia and New York around the turn of the century, but use of engines for manufacturing was rare (47). The first U.S. textile mills, in Rhode Island in the 1790s and Massachusetts in the 1810s, were all powered by water wheels (20). Steam engines did not become an important component of U.S. industrial motive power til the 1860s (1).

Industrial energy use ballooned after the Civil War, in a period of rapid expansion of infrastructure and industry in the Northeast and Midwest (24, 35). U.S. industrial energy throughout the 19th century continued to be dominated by process heat for steelmaking (see Section 7.1), but coal was now also used to drive steam engines. By the turn of the century, coal utterly dominated energy use in U.S. industry. Industrial coal use continued rising until the Great Depression, when steelmaking came to a temporary near halt, and then began a long decline in both per capita and absolute terms. Total industrial energy use grew because of addition of petroleum and natural gas, which powered the rise of the U.S. chemicals industry and oil refining. Electric motors also replaced steam engines for motive power. U.S. per capita industrial energy use peaked just before the 1973 OPEC crisis, dropped even more abruptly after the 1979 Iranian revolution, and never recovered. The following four decades of decline was driven mostly by the gradual extirpation of coal. By the early 2000s, industrial use of coal sank below that of biomass for the first time since 1857. This decline almost certainly reflects not efficiency gains or fuel substitutions but instead “deindustrialization” and the shifting of energy-intensive materials manufacturing offshore (15, 16). The tiny amount of remaining direct industrial coal use in 2019 is concentrated in still-shrinking U.S. steelmaking.

In this inventory we do not yet separately track manufactured gas. From the mid-19th century it was predominantly made with bituminous coal, and its usage is assigned to industry, so it appears as part of the fuel stream “coal → industrial”. After ∼1900, most natural gas was used in industry, but in the 19th century its use was predominantly for residential, commercial, and municipal lighting. while manufactured gas was negligible in terms of total U.S. energy consumption, it played an important role for these particular niche uses.

3.4. Transportation. By our definition, the transportation sector experienced two energy transitions over the period of study, from biofuel to coal (1871–1881) and coal to petroleum (1921–1948). Transportation energy is shown in per capita and fractional terms in Figure S9 below.

While the industrial sector experienced the largest growth in per capita energy use across the past two centuries of the U.S. history, the transportation sector experienced the most *consistent* growth. Transportation is also the sector with the simplest energy transitions. The sector has been successively dominated by three different fuels over two centuries – first biomass, then coal, and finally petroleum – with periods of dominance separated by brief moments of transition.

Early transportation was dominated by biomass (horses) on land, and by wind (sailing ships) at sea. Note that while feed for horses outweighed the amount of wind energy captured by sails, this comparison understates the importance of marine transportation to the early American economy. American roads were abysmal and goods traveled mostly by water, but ships require less power to haul cargo over a given distance than does any form of overland transport (5).

This paradigm began to change in the 1810s with the American invention of the steamboat for river transport. While the English development of steam began with stationary pumping engines, American interest focused on whether steam could allow U.S. rivers to becomes a cargo-transport network (47). Although the first steamboats burnt wood, they also provided an important early market for coal, especially as their enormous energy needs stripped the riversides of timber (48, 49).[5] The first railroads in the 1830s provided another market for coal, but primarily facilitated its use in household heating by carrying it to locations far from the mines. The movement toward a coal-based transportation system accelerated only after the Civil War when the rail system was rapidly expanded. In 1860, the U.S. transportation sector was 70% biomass-powered and less than 10% coal-powered; by 1885 these numbers had nearly flipped. By our definition of the transition period, the biomass-to-coal transition took only 10 years to complete.

The new transportation paradigm of coal-fueled railroads continued for about 40 years before an abrupt pivot to petroleum. The shift involved a crisis in the 1910s of the intertwined coal and railroad businesses. (Coal made up a third of U.S. rail freight in 1918, and railroads themselves owned much of coal production (50, 51).) The previous decade had seen a dramatic coal boom, during which poor labor conditions led to violent strikes (52). World War I produced spiraling prices and government takeover of coal mines and railroads to ensure supply (along with military suppression of labor actions); prices stayed high through the post-war crash in production (51–54). Railroad demand for coal then dropped sharply, both because freight transport fell and also because railroads sought to reduce dependence on coal by refitting steam locomotives to burn fuel oil instead (55). By the 1930s, locomotives and ships were abandoning the steam engine for diesel-powered internal combustion engines, and rising numbers of gasoline-powered automobiles contributed to petroleum demand. Use of automobiles and trucks was facilitated by expansion of highways and rural roads in the 1890s–1910s and gas stations from the mid-1910s–1930s (56), and exploded in the late 1950s after the construction of the federal interstate highway system. The 1950s also saw the retirement of the last coal-powered locomotives. From this point on, the U.S. transportation sector has been almost entirely oil powered; no other

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[3] These numbers are based on Census Report on Manufactures (1) figures for total horsepower and a plausible range of 10–25% efficiency in the average industrial engine (45).

[4] This estimate is based on a reported 63% of industrial electricity used in electric motors in 1994(46), and our own estimate that 32% of all industrial energy was supplied by electricity at this time.

[5] The *Chicago Tribune* estimated in 1848 that the one of the Lake Michigan steamboats, the *Empire*, burnt the equivalent of 234 acres of timber each season (48)

fuels have played a significant role. The early twentieth century saw a boom in electric streetcars, and natural gas has powered some trucks and buses since the 1950s, but neither ever exceeded a 5% share of transportation energy use. Corn-based ethanol that is blended with gasoline has just in the last decade reached a 5% share.

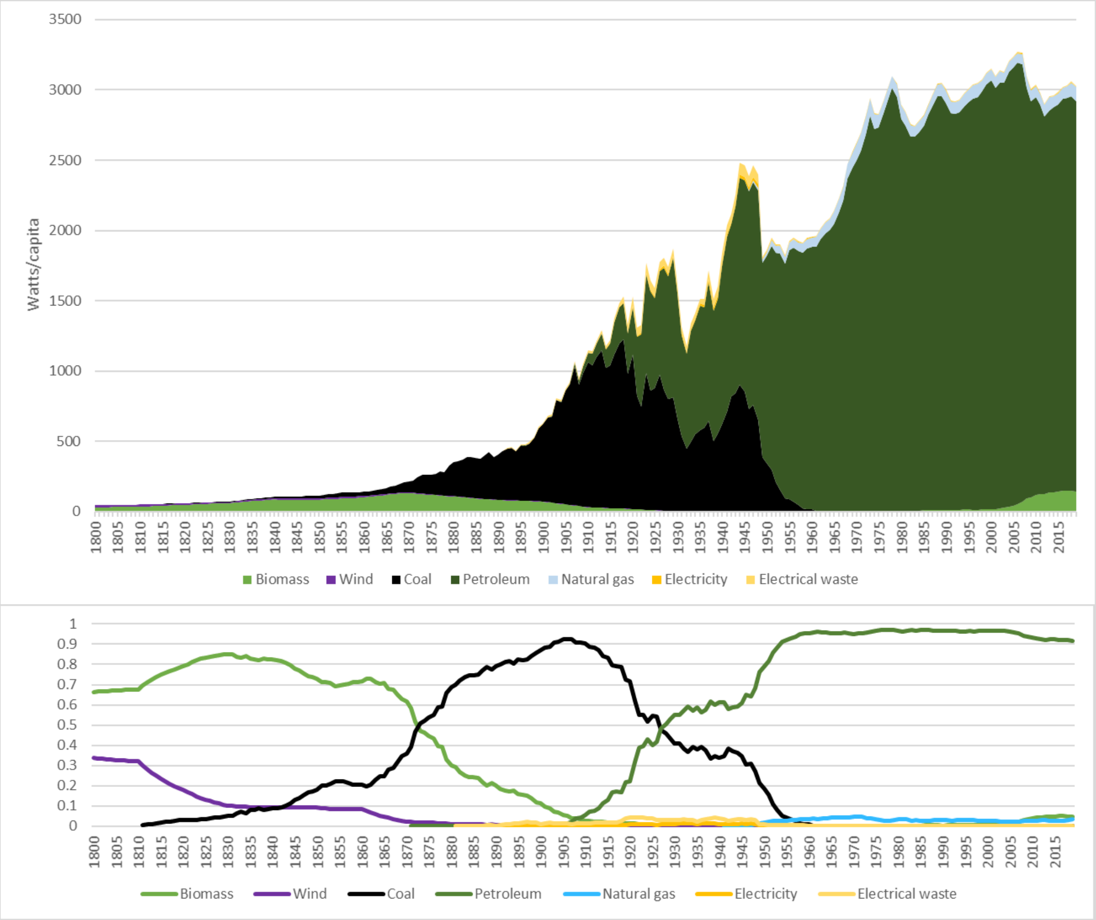

Fig. S9. Fuels used in the transportation sector, as a stacked bar graph in W/cap. (top) and as fuel shares (bottom), repeating part of manuscript Figure 5. By our definition, transportation has undergone two periods of transition: 1871–1881 (from biomass to coal) and 1921–1948 (from coal to petroleum). The sharpest declines in per capita use are the Great Depression in the 1930s and the end of the Second World War in 1945–1946, as we bookkeep armed forces vehicle use under transportation. (Sharpness of 1910 peak may be an artifact of interpolating decadal estimates.) The early rise of petroleum for transportation in the 1910s is not necessarily due to internal combustion engines, but includes conversion of steam locomotives to burn fuel oil instead of coal in external combustion (55). Early "biomass" here includes both animal feed for horses used in transportation and fuelwood used in steamboats and railroads. More recent biomass is corn-based ethanol that is blended with gasoline. For details on individual sources, see Sections 7.1, 7.3, 7.4, 7.5, 7.6, 7.9, 7.11, 7.12.

3.5. Electricity Generation. The use of different fuels for electricity generation can be evaluated either of two ways: as primary energy *inputs*, or as electricity *outputs*. In Figure S10 below we show both perspectives. In assessing transitions in the electric sector, we consider outputs (i.e. the contribution of each source to generating electricity). With this definition, electricity generation has experienced a major recent energy transition since 2012, away from coal to natural gas (Figure S10).

Considering inputs or outputs yield different results because processes for generating electricity from different sources also have different efficiencies. Thermal generation – burning a fuel for heat in an engine or turbine that spins a generator - is necessarily wasteful, and early coal-fired power plants recovered under 10% of fuel energy content as electricity. Coal therefore made up 90% of energy inputs to the electric sector from its beginnings (Figure S10, top), even though hydropower initially produced roughly as much electricity (Figure S10, bottom).

The rise of coal to ascendance over hydroelectricity took nearly half a century. During this period both technologies expanded at similar rates, with the federal government playing a major role in dam-building via the Army Corps of Engineers and the Tennessee Valley Authority. That era necessarily ended eventually given the finite supply of U.S. rivers. From the 1950s–1970s, growth in electricity generation (×3 in per capita terms) was driven almost entirely by coal (Figure S11) and coal maintained dominance in the electric sector for over half a century.

Several fuels made appearances but did not achieve much penetration. Oil-fired plants were built in the 1960s, but were rendered both uneconomical and illegal by the price spikes following the OPEC crisis. (The federal Industrial Fuel Use and Power Plant Act of 1978, which forbade new construction of electricity generation based on oil or natural gas, until its effective

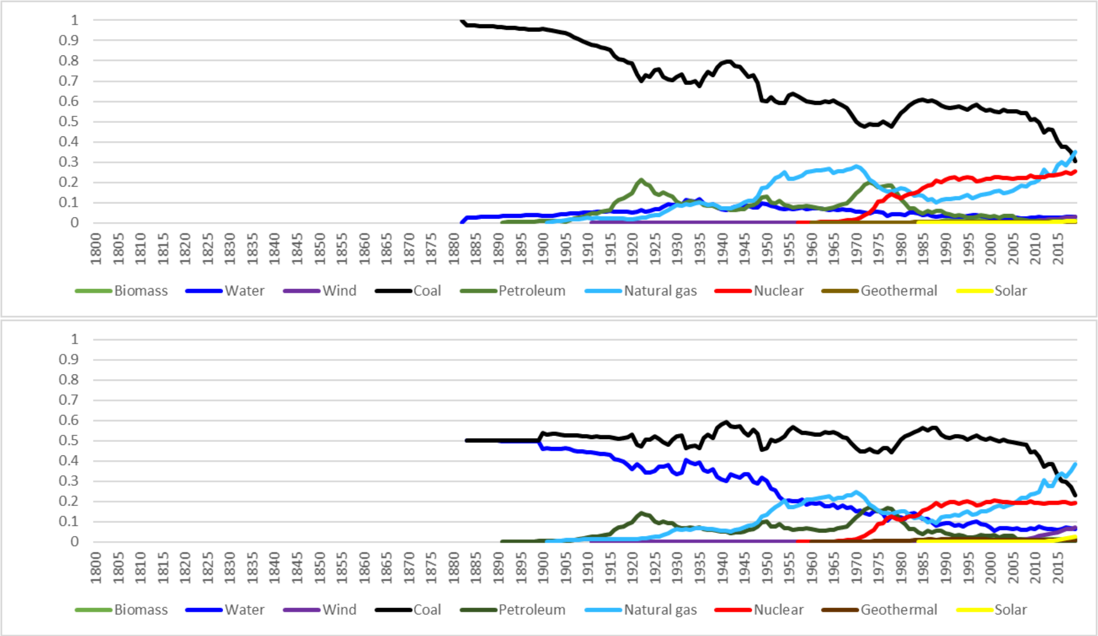

Fig. S10. Fractional use of fuels in electricity generation, as share of inputs (top) and as share of electricity outputs (bottom). By our definition, electricity generation is undergoing one energy transition beginning in 2012 (from coal to natural gas). Inefficient early coal-burning power plants used high input energy but produced little electrical output relative to hydro. (Hydro and other non-thermal sources are assumed efficiency 1 in this work.) The rise of nuclear in the 1970s is stalled by the 1979 Three Mile Island accident. The sharp drop in natural gas and oil share in the late 1970s is driven by post-OPEC conservation measures, including the 1978 Power Plant and Industrial Fuel Use Act that forbade their use in new electricity plants. More recently natural gas has been replacing coal, aided by cheap gas since the advent of modern fracking in about 2003.

repeal in 1987.) In the 1970s, nuclear power was touted as the fuel of the future, but its growth was stalled by the Three Mile Island meltdown in 1979 (22). After the accident, some plants already under construction were completed, but no new nuclear permits were issued again until 2012. The contribution of nuclear to U.S. electricity was therefore flat since the mid-1980s and is now declining as aging plants are retired.

In the last decades, the electric sector has been upended by the development of modern hydraulic fracturing, which has produced a glut of cheap natural gas. Coal use fell precipitously from the moment it lost its price advantage, with coal power plants downcycled or shut down. Coal fell from a 56 to 30% share of electricity generation in only 17 years, with natural gas rising to replace it. By our definition, U.S. electricity generation has been in transition since 2012, and is currently half-way to completion. The timing of the change is consistent with prior historical energy transitions.

Many of the new natural gas plants coming on-line in the last decade are ultra-efficient combined cycle plants (57). The switch from coal to natural gas has therefore led to a sharp drop in energy inputs to electricity generation (Figure S11, top) even while electricity production itself has been fairly stable (Figure S11, bottom). Per capita input energy to the electrical sector dropped by 18% between 2003–2019, even though electricity production dropped by only 3%. In total about half the drop in U.S. primary energy use in the 2000s (Figures S1 and S2) is due to the increased efficiency of electrical generation.

Non-hydro renewable electricity generation (wind and solar) makes a small contribution to this trend. Wind and solar have risen strongly in fractional terms since the 1990s, aided in part by federal and state subsidies, but both remain relatively minor contributors. It is also not clear that their upward trend promises an era of carbon-free electricity, because at current rates of growth, increases in wind and solar electricity may not be sufficient to outweigh the coming shutdown of aged nuclear plants.

3.5.1. Efficiency of electricity generation over time. Our historical data allows us derive the evolving efficiency of both the overall U.S. electrical sector and of thermal generation in particular (Figure S12). A prior estimate was published by Vaclav Smil (58), but without detailed documentation; the EIA has estimates only as far back as 1949. With our data, we can reliably compute efficiencies as early as 1920 directly by taking the ratio of electricity output to fuel input. We extract by subtraction the electricity produced from all combustion sources (coal, gas, oil, and biomass) since we have separate estimates of electricity from individual non-combustion sources (hydro, wind). Dividing by fuel inputs then gives the combined efficiency of all thermal generation. The earliest systems of coal-fired reciprocating engines connected to generators via belt drive appear to have efficiency of less than 10%; this value is consistent with (58). While our historical data is only comprehensive after 1920, we are able to draw conclusions about the second quarter of the twentieth century. Thermal efficiencies began to rise in the early 1900s with the introduction of the first steam turbines and continued to climb along with steam temperatures and pressures (58), reaching around 25% by 1949. At the same time, the *overall* efficiency of the whole electrical sector fell, as the buildup of power plants meant that coal's role grew relative to hydro (whose efficiency we book-keep as 1).

From 1949, we can use fine-grained data from the EIA to separately track the efficiency of generation from coal, natural gas, and petroleum. The EIA also provides direct estimates of the efficiencies of steam turbines used in nuclear power plants

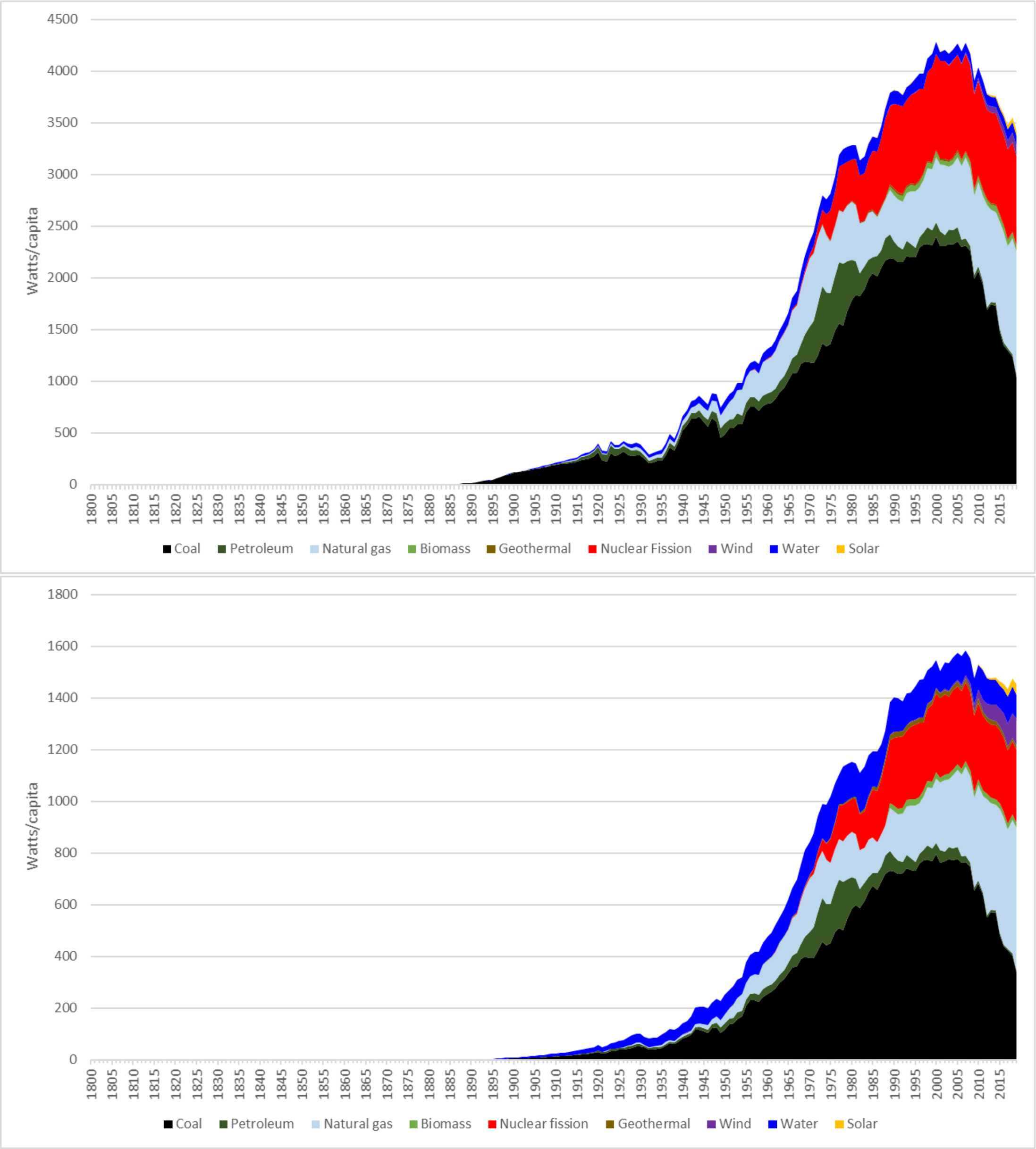

Fig. S11. Fuels used in the electrical generation sector, as inputs in Watts per capita of primary energy (top), and as contributions of electricity produced, in Watts per capita of electricity (bottom). The ratio of values in bottom and top graphs is the overall efficiency of electricity generation. Because we book-keep non-thermal generation (hydro, wind, and solar) as efficiency 1, these appear as relatively small primary energy inputs. For consistency with other sectoral charts, x-axis starts at 1800, but commercial electricity production began only in 1882. The expansion of coal in electrical generation corresponds with its decline in all other sectors. Sharp drops in oil and natural gas use occur after price shocks in 1973 (OPEC crisis) and 1979 (Iranian revolution). For further notes on how these figures are derived, see Notes 7.1,7.10,7.11,7.13,7.13.3.

(2). From 1949 through the mid-1980s, all these fuels had similar generation efficiencies, possibly because early use of gas for electricity generation involved external combustion and steam. All efficiencies rose into the early 1960s and then plateaued, consistent with estimates of the evolution of steam turbine temperature, pressure, and total size (58). Gas generation efficiency jumped in the late 1980s with a burst of construction of new gas turbines (59), and rose again after 2003 as cheap fracked gas was increasingly used in combined-cycle plants (57). (That is, the price drop allowed gas to be used in the most efficient plants, which operate continuously, rather than in less-efficient peakers, which are turned on only when electricity prices are highest.)

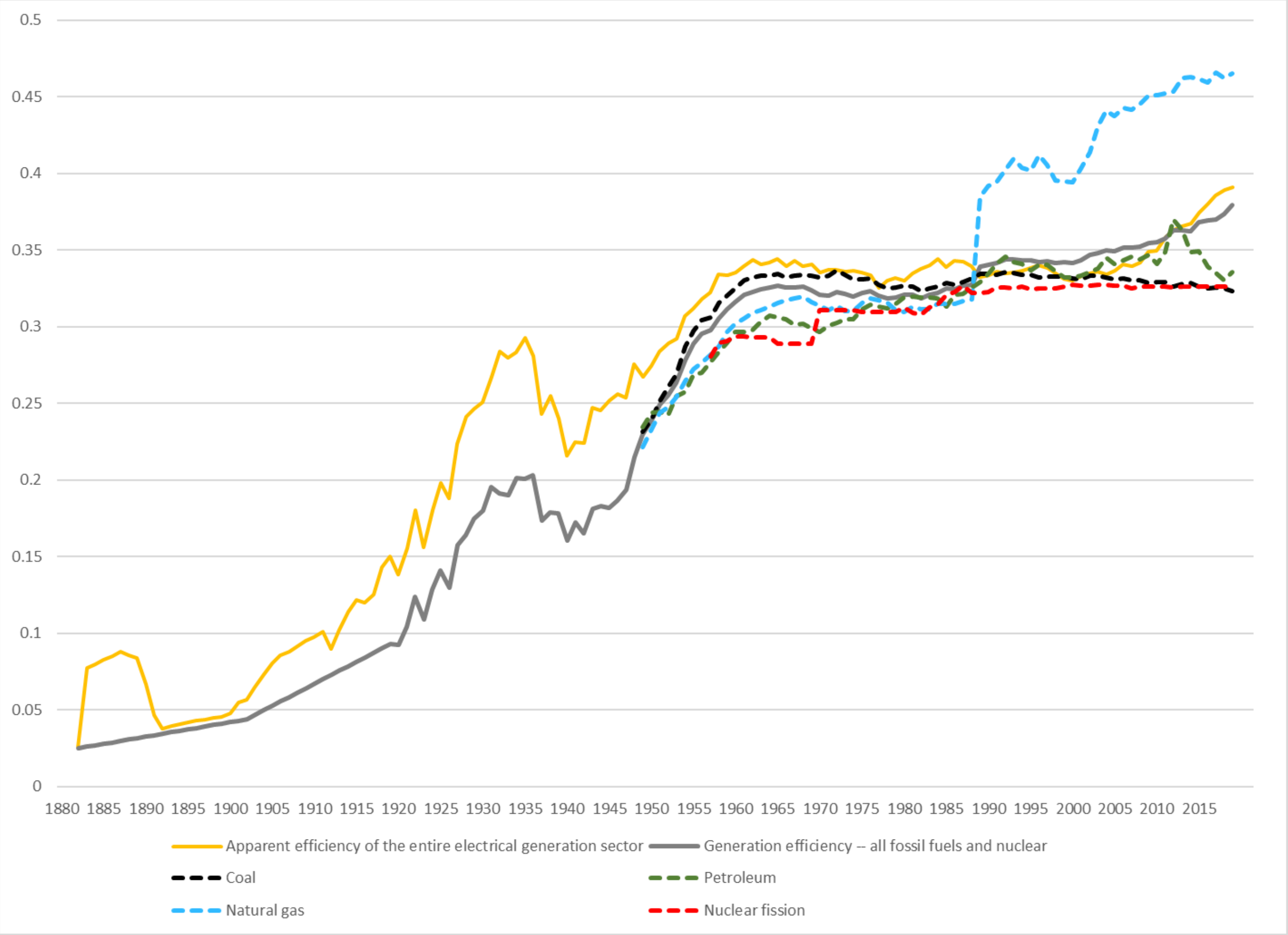

Fig. S12. Efficiency of electricity generation, 1880–2019, estimated from our dataset. Before 1949 we show efficiencies for all thermal generation (gray) and for the electrical sector as a whole, including non-thermal renewables at efficiency 1 (orange). After 1949, we also separately show the efficiency of generation by different fuel types: coal (black), natural gas (blue), petroleum (green), and nuclear (red). The dotted lines indicate extremely sparse data. Because values are unreliable in the first three decades of electricity production, we report this data only as a preliminary estimate, rather than a result. (See Section 7.12.) Complete data is available for 1882, 1902, and annually from 1919 on, although between 1919–1949, electricity is recorded annually and fuels for generation are recorded inconsistently and we occasionally must interpolate between five year intervals (especially for petroleum and natural gas); see Section 7.12. The overall efficiency of the electrical sector shows an early drop in the 1880s–1910s that results from increasing use of coal vs. hydro, and a recent rise since the 2000s that results from increasing use of cheap natural gas in combined-cycle power plants. The aggregate efficiency of U.S. natural gas plants largely follows that of coal until the 1980s (presumably because gas was first used for external combustion and steam), then reflects the efficiency of gas turbines until the 2000s; then rises again with the increased use of gas in combined-cycle plants.

4. Results: Energy Intensity of the Economy

The energy intensity of the economy – the GDP generated per unit of energy consumed – is a common metric for measuring how productive a society's energy use is. In Figure 1 of the main text of this work, we show the evolving intensity for the U.S. from this study, and compare to selected countries from 1971 from a World Bank dataset (60) and to an estimate of the Netherlands' historical energy use from 1815, constructed as part of the Long-term Energy and Growth project (9). The modern countries shown, and the historical Netherlands, tend to fall between \$4-12 per Watt per year. That is, each Watt of energy used produces approximately \$4 to \$12 in economic value (in 2011 dollars).

In Section 4.1 below we show further comparisons: we compare World Bank and historical estimates (Figure S13, we show those World Bank countries omitted from Figure 1 (Figure S14) and we show historical estimates from other countries (Figure S15). In Section 4.2, we should the evolution of U.S. energy intensity if residential energy is excluded from the measure. Since early U.S. energy use is dominated by residential usage, this change of definition produces a very different perspective.

4.1. Energy Intensity Comparisons.

Validation. As a partial cross-validation exercise, we compare the historical energy intensity trajectories from Figure 1 for the U.S. and the Netherlands with their equivalent World Bank timeseries (Figure S13). As in manuscript Figure 1, the evolution of GDP and energy use are shown on a log-log plot. Note that in all cases we use the same estimates of GDP, so the comparison is only of estimated primary energy use. The estimates are broadly comparable, with the World Bank energy use for the U.S. roughly 10% below that of this work, and that for the Netherlands roughly 20% above that of (9). Deviations associated with the 1970s energy crises appear similar in all datasets. Some differences may arise from how the different datasets book-keep primary energy from renewables and nuclear energy. We assume a thermodynamic efficiency for the steam turbines used in nuclear power plants, but assign an efficiency of 1 to hydro, solar, and wind (see 6.2.2). Omitting the nuclear efficiency would lower an estimate of primary energy use; assigning efficiencies to hydro, wind, and solar would raise it.

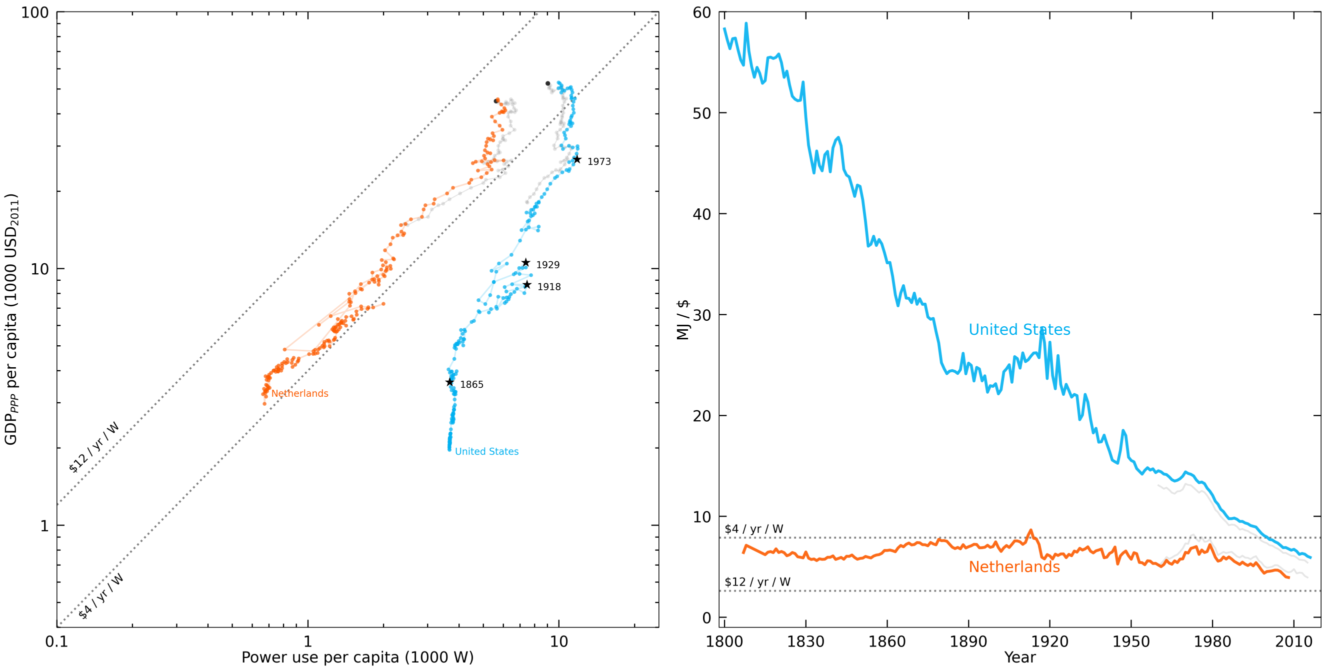

Fig. S13. Historical energy intensity estimates for the U.S. (1800–2019, this work) and the Netherlands (1815–2008, (9)) compared to those from the World Bank (60). Date markers for the U.S. are as in manuscript Figure 1. Because all timeseries use GDP from the same database (61), any differences between historical and World Bank estimates are due to energy use. Estimates are broadly consistent, but differ by $\sim$10% for the U.S. and $\sim$20% for the Netherlands. Trends in evolution of energy intensity are not affected.

Excluded countries. In manuscript Figure 1, we exclude four categories of countries from the World Bank data shown. *Planned economies* might generally be expected to be less efficient, i.e. to have lower GDP per energy used and therefore higher energy intensity. *Energy producing countries* may have anomalous high energy intensity, if cheap local prices lead to excess use, or low energy intensity if low energy extraction costs mean that revenue is high relative to energy spent. *Small countries (<4M population)* might be expected to exhibit low energy intensity, if their economies are concentrated in e.g. services or finance rather than in energy-intensive industry. We also group *sub-Saharan countries* for convenience, since many sub-Saharan countries have suffered conflicts or political instability, and most experienced relatively recent transitions from colonial control. Individual countries may have have diverse experiences that would be reflected in their energy intensities. We do not attempt to group all colonial countries (e.g. India, Vietnam) due to the ambiguity of the category's boundaries.

In figure S14, we show GDP vs. energy use for all countries in the World Bank dataset, highlighting separately each of the four excluded categories. Patterns in those countries are discussed below.

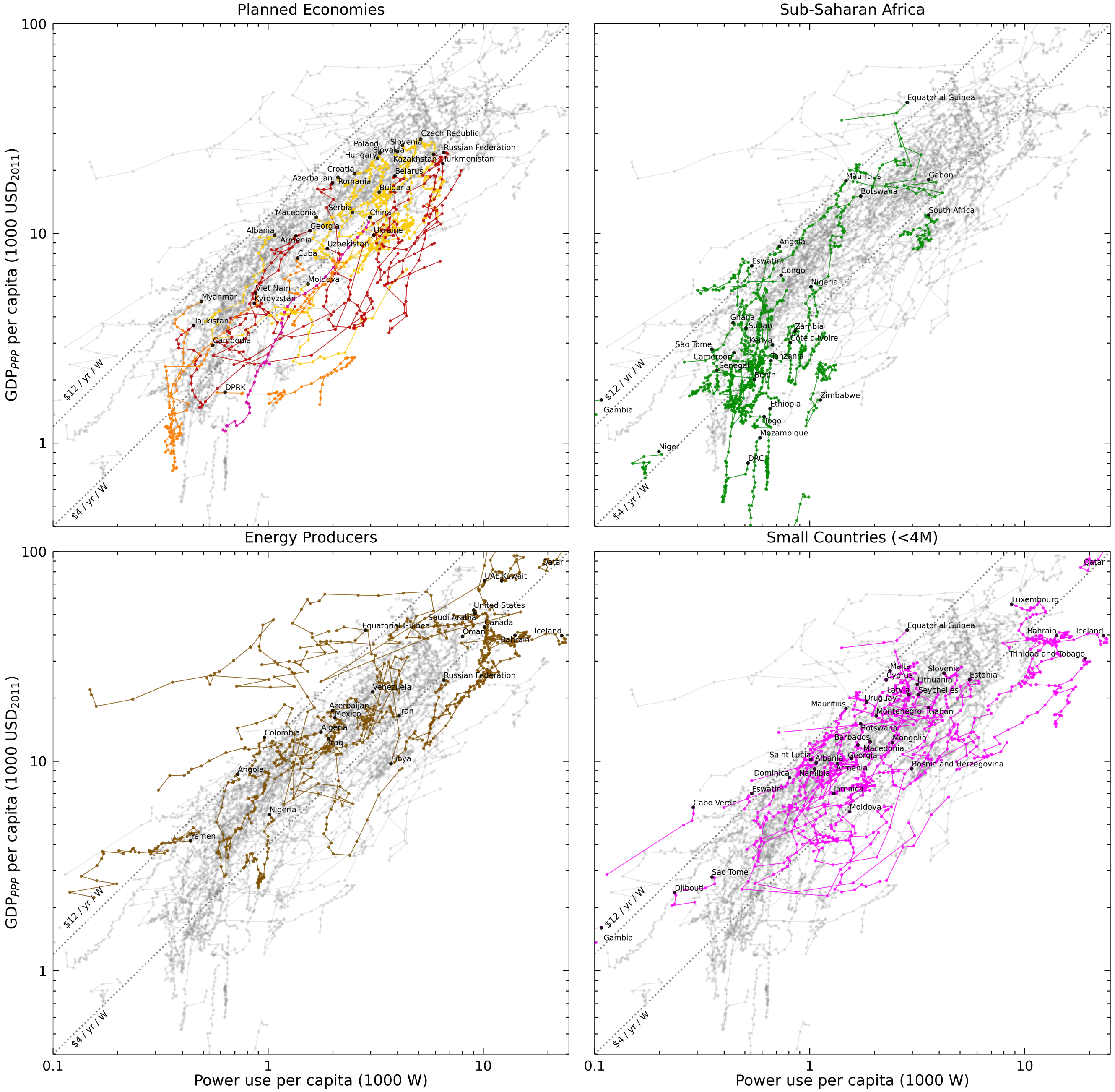

Fig. S14. GDP vs. energy evolution, all countries, ca. 1971–2019, with energy use from the World Bank (60) and GDP from the Maddison Historical Statistics (61). As in left panel of manuscript Figure 1, but now including all 165 countries with reported data on energy and GDP rather than the 58 countries of Figure 1 (59 including the U.S.). Panels highlight the various groups of countries originally excluded. *Top left:* 29 primarily state-planned economies, grouped as former Soviet Union (red, 11), former East Bloc (gold, 12), China (purple), and other (orange, 5). *Top right:* 38 sub-Saharan African countries (green); *Bottom left:* 22 major energy-producing countries (brown); *Bottom right:* 39 small countries (< 4 million people in 2019) (pink). Some countries appear in multiple categories: e.g. Equatorial Guinea is both a small country and an energy producer. Energy producers include the top-20 oil exporters by volume, other than Norway and the U.K, which derive only a small part of their economy from oil; plus Libya, Equatorial Guinea, Yemen, and Bahrein, whose economies are overwhelmingly dominated by oil production; plus Iceland whose geothermal energy has attracted energy-intensive industries (62). Note that not all countries have data extending to 1971.

Planned economies. Planned economies in general tend to have high energy intensity. As expected, countries associated with the former Soviet Union (red and gold) tend to have anomalously high energy use per GDP at the beginning of their timeseries, but grow more efficient over time. Most East Bloc and FSU timeseries begin in the 1990s with the breakup of the Soviet Union. China (purple) has also lowered its energy intensity over time and is now on the $4/yr/W line.

Sub-Saharan African countries: Many sub-Saharan African countries have experienced political instability or conflict; these tend to have both low incomes and high energy intensity (data in lower left of figure). Some countries that experienced severe conflicts regressed in income before more recently rebounding (e.g. D.R.C., Mozambique; Mozambique GDP drops off-scale during the 1977–1992 civil war, falling below \$300/yr/person). Many countries experienced a strong growth from an initial condition of inefficiency (high energy intensity), so that income increased without much increase in energy use; these may be cases of post-colonial recovery. Some countries that began in the \$4–12/yr/W range (e.g. Senegal, Ghana, Mauritius) show "typical" evolution in which income and energy use grow in parallel.

Energy producing countries: Major energy producers display strong variation in energy intensity, as expected. Energy is both cheap (enabling wastefulness) and gives a high energy return on energy investment (producing high income per energy expended). Note that both the U.S. and Canada are included in this category. The highest energy intensity country at present is Iceland, likely because their low-cost geothermal electricity has attracted energy-intensive aluminum production. Incomes for Kuwait, Qatar and the UAE rise off-scale when oil prices are high.

Small countries: Small countries ($<$ 4 million population in 2019) are also diverse in their energy intensities. Many of these countries are also members of other categories (energy producers, or state-planned economies).

Historical estimates. Historical studies over the last decade have produced a wealth of estimates of primary energy use from the 19th century in different countries. We show data from the Long-term Energy and Growth project in Figure S15 for comparison to the United States data of this work. While most of the historical timeseries remain relatively flat and close to or even within the \$4–12/yr/W range, five countries stand out. Three of these show very high early energy intensities that drop over time: the U.S. Canada, and Sweden, with the U.S. and Canada significantly higher. All three are cold-winter countries that would be expected to have high residential energy use. Differences might be explained by greater stocks of timber in colonial North America (63, 64), which discouraged conservation (26, 36). North Americans also typically used open fireplaces and had limited access to the efficient stoves that were more common in Sweden (11, 13).

The remaining two countries with strong trends in energy intensity are the U.K. and Germany. Both show more of a U-shaped pattern of evolution, as is expected in some theories that hold that energy intensity should be higher during periods of industrialization (65). The U.K. led the Industrial Revolution, and Germany industrialized heavily in the late 1800s. German energy intensity also spikes after both world wars, likely because of drops in income during postwar economic crises.

Many countries here show the general trend of decline in energy intensity since the late 1970s, that was also seen in the World Bank data of manuscript Figure 1. This decline is the subject of extensive research (e.g. (66, 67)). The results is that energy intensity across countries converges over time, though the U.S. and Canada remain high outliers. In the World Bank data of manuscript Figure 1 (which excludes Canada as a major energy producer), the only countries with higher energy intensity than the U.S. in 2019 are Nepal and Haiti.

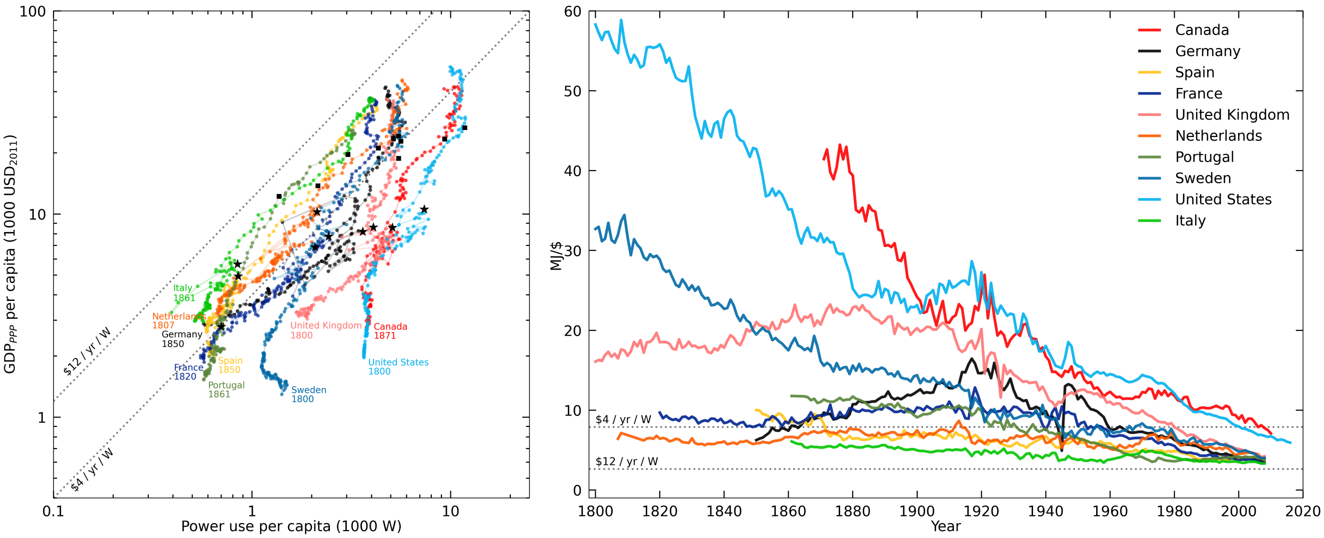

Fig. S15. Energy intensity time series, 1800s–2019. As in manuscript Figure 1 but here showing nearly all historical timeseries of energy use from the Long-term Energy and Growth project (9–11, 65, 68, 69). GDP in all cases is from the Maddison Historical Statistics (61). We show all countries available other than Uruguay, whose estimates are noisy, and Czechia and Slovakia. We omit Canadian data before 1870 because GDP estimates are sparse. The start year for each timeseries is noted. Symbols mark two time points on each timeseries: the start of the Great Depression in 1929 (star) and the OPEC oil crisis of 1973 (square), which began a period of high oil prices. A similar figure using these data was shown by (70).

4.2. U.S. Energy Intensity without Residential Use.

The United States is anomalous in that its energy intensity has declined over its entire history, for 220 years. This trend has been interpreted as implying structural economic changes (40, 70), and is commonly projected forward in policy analysis models that assess approaches for decarbonizing the energy system. Our dataset shows that the long-term trend is dominated by energy use for household heating, which involves categories not counted in the economy. Further potential future energy savings in the residential sector have also diminished as other sectors have grown in importance.

It may therefore be more useful to redefine energy intensity as *non-residential* energy use divided by GDP. This metric omits the distortions introduced by domestic energy use and may better reflect fundamental economic changes. Figure S16 shows the different perspective provided by this alternate definition. When residential energy is omitted, the evolution of U.S. energy intensity appears more similar to that of countries like the U.K. and Germany in Figure S15, with a maximum at the time of most intensive industrialization. This perspective also more clearly shows the change in regimes after the energy crises of the 1970s.

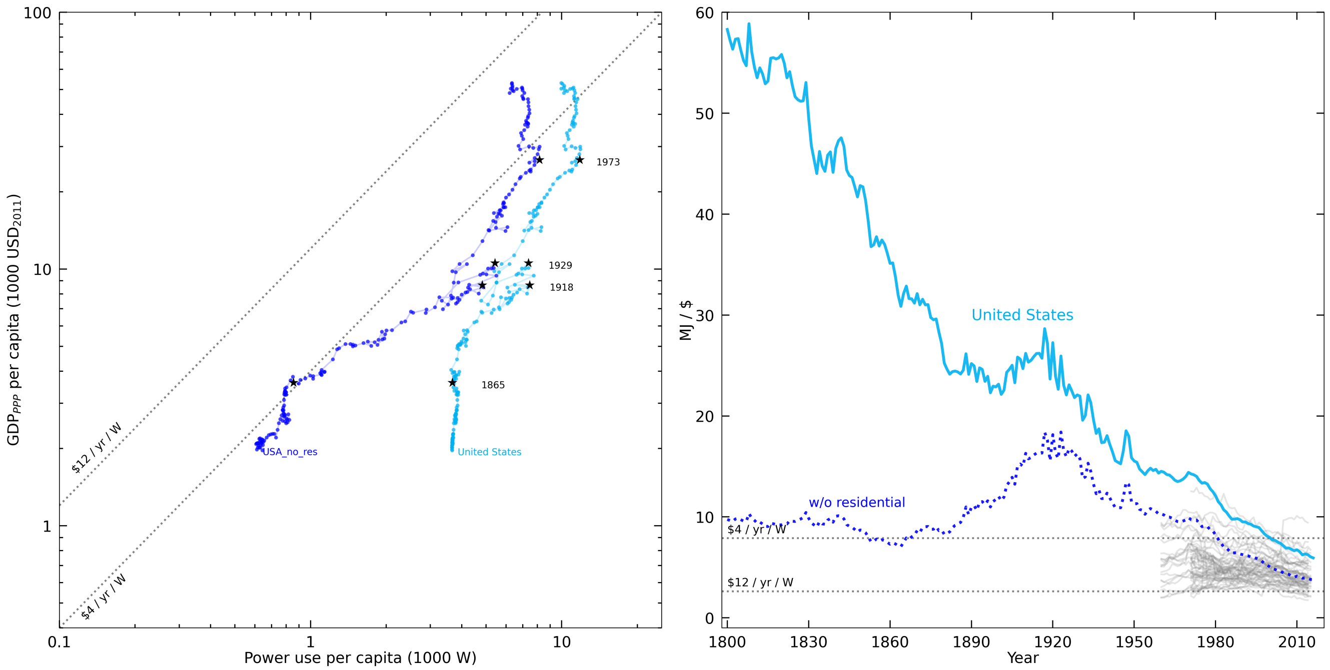

Fig. S16. Evolution U.S. energy use including (light blue) and omitting (dark blue) residential energy. Left panel shows energy use vs. GDP per capita; right panel shows their ratio, the energy intensity, in units of MJ of energy per dollar GDP. Energy use is from this work and GDP from Maddison Historical Statistics (61). Note that energy use estimates are decadal only before 1920, and are linearly interpolated; GDP estimates are annual. Stars mark dates of key points in U.S. energy history. The anomalous high early American energy intensity is driven by residential usage. With residential energy excluded, energy intensity follows an “inverted-U” curve suggested as characteristic of industrial countries, with a peak in approximately 1910 (65). This perspective also more clearly shows that identified key points in U.S. energy history are associated with changes in energy intensity. The Civil War in 1865 marks the beginning of industrialization, 1910 marks the peak of industrialization, the Great Depression following 1929 is a time of lowered income and therefore anomalously high energy intensity (followed by a recovery during WWII), and the energy crises of the 1970s bring in a new regime. From about 1973 onwards, U.S. per capita energy use has declined even while incomes increased.

These results highlight that while the concept of energy intensity can be useful in understanding the relationship of national economies to energy systems, it should be applied with care. Benchmarking energy use to GDP requires considering both how energy is used and what GDP is measuring. Because GDP measures economic activity as the sum of monetary transactions, it is problematic when used in the context of household activities which are not remunerated. It is also an imperfect measure of general economic well-being (71). Finally, it is useful to remember that trends may reflect not fundamental laws but historical accidents. The United State’s anomalous energy evolution may be less the result of some intrinsic inefficiency than the accidental legacy of cheap and abundant fuel wood.

5. Results: Omitted Energy Flows

In this section we discuss two energy sources omitted from our dataset, human labor (Section 5.1) and natural ice for refrigeration (Section 5.2). Both are relatively small.

5.1. Human Labor.

We omit human labor in these statistics for two principal reasons. First, human labor is hard to apportion by sector. Although the Census asked respondents about their industry of gainfully employment as early as 1820, many work categories overlap sectors. The relative contributions to household labor and agriculture are especially difficult to differentiate. Second, humans comprise only a tiny fraction of the overall energy system. Even in the early nineteenth century, input energy to humans – their food - makes up less than 5% of total U.S. energy use.

It is worthwhile, however, to explore whether inclusion of humans might alter our image of the energy economy. For this purpose we count the number of workers from the Census (1), and assign all workers to the sector we judge the best fit with the Census employment category. To provide an upper bound for the contribution of humans, we assume all people not gainfully employed are household laborers, including children. For enslaved people, who are counted in the Census but not assigned employment categories, we use an estimate from Fogel and Engerman (1995) of the proportion of enslaved people occupied in households, agriculture, or as 'artisans' (which we assign to industry) (72). For the example year of 1860, this processes classifies a bit under half of the U.S. population in agriculture, a similar proportion in the household, less than 10% in commercial and industry combined, and barely over a percent in transportation. To establish an upper bound on energy inputs we assume a diet of 3000 kcal/day (145 W/cap.) for all humans.

Results imply that even in a pre-industrial American economy, the bulk of energy in every sector was derived from sources outside of the human body (Figure S17). Early U.S. primary energy consumption is dominated by burning of fuel for heat, and even in those sectors with little demand for thermal energy (agriculture and transportation), humans make only a minor contribution, as most mechanical work had long been outsourced to animals or wind.

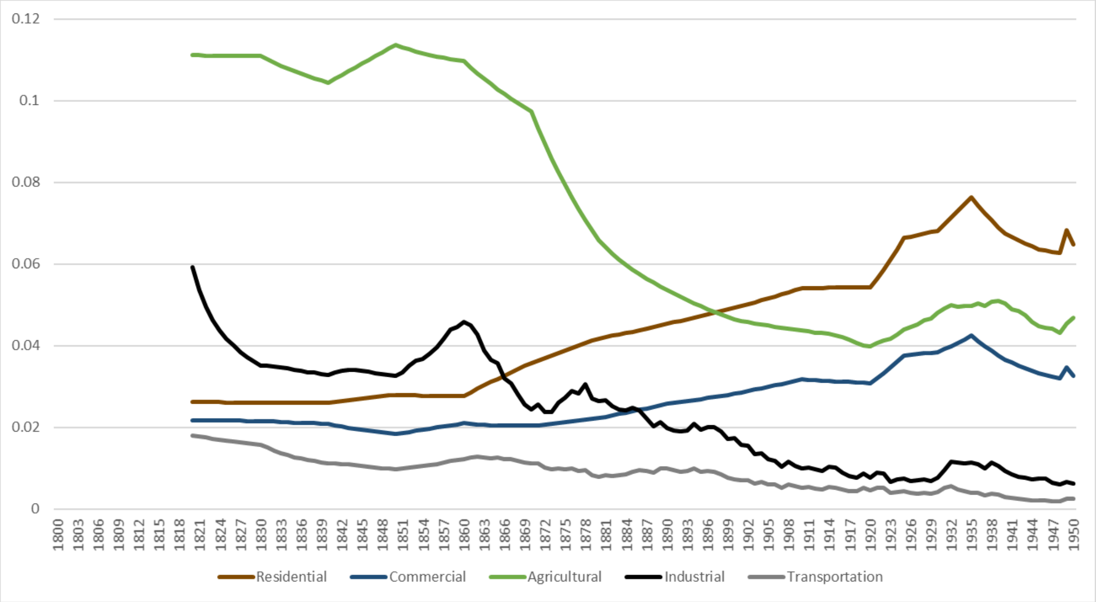

Fig. S17. Proportion of human food to total sectoral energy use, 1820–1950. Calculation of human energy inputs is described in text. Note that industrial energy use may be underestimated, and the human contribution overestimated, as we do not track draft animals employed in industry. In our dataset all non-agricultural draft animals are categorized under transportation, including e.g. horses used for in construction or logging.

It is worthwhile to quantitatively estimate the human contribution to mechanical work (also known as "motive power"). Motive power in the early 19th century was provided largely by animals, to a lesser extent by humans, waterwheels, and sails, and to a very minor extent by steam engines. Since animals and humans have similar efficiencies of conversion of feed to mechanical work (17), we can directly compare estimates of food for humans and animals. In the early nineteenth century, input energy to horses, oxen, and mules is over 3× that to humans: ∼15% vs. ∼5% of total U.S. energy use, respectively. In agriculture, the dominance of draft animals is still larger, with draft animal inputs of ∼8× those for all human labor, even inclusive of enslaved children.[6] Even in the most generous interpretation, humans were relatively unimportant in a pre-industrial economy for the power they provided. The value in a human laborer came from manual dexterity and reasoning. While many tasks were already mechanized in the mid-19th century, others still required skills that only humans could perform.

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[6] In our accounting, enslaved people made up about 40% of agricultural labor force in 1850.

One question that may be asked of this data set is what insight energy data can shed on slavery. Slave labor was critical for cultivation of cotton, a key commodity in the American economy: it was the most highly capitalized and by some measures the most valuable product in the United States. Cotton was central to the growth of the United States, and through textiles to its industrialization. The estimates above suggest, reasonably enough, that the added value slaves brought to the economy was not simply their additional mechanical work but rather their uniquely human attributes. Picking cotton was a difficult, labor-intensive job, but most importantly, it required human hands until mechanical cotton-pickers could be devised. These arose only in the 1920s, during the Great Migration era, when a combination of labor shortages due to fleeing Black sharecroppers and technological innovations combined to finally mechanize the cotton industry (73, 74).

5.2. Natural Ice.

The mention of ice as a primary energy source may seem incongruous. But before the twentieth century, the only practical means of cooling or refrigeration was through natural ice cut from frozen lakes and rivers (70). Especially in the late nineteenth and early twentieth century, natural ice played an important role in refrigeration of food and drink both in households and in industry. The Chicago meatpacking fortunes of the late 19th century, for example, were made by shipping beef to Eastern cities in boxcars refrigerated with natural ice.

Ice was primarily harvested from northern U.S. rivers and lakes, especially in New York and New England but also in Wisconsin and Michigan for the Midwest market. It was then shipped by boat and railroad across the country. In most cities, large storage facilities would keep ice through the whole year, and ice was purchased from distributors for household use in iceboxes. By the turn of the century, the invention of mechanical refrigeration allowed expansion of U.S. energy use for cooling. Production of manufactured ice at steam-powered facilities had almost replaced natural ice use by the 1920s, (75), and by the 1930s, electrification allowed wider adoption of direct cooling on site in equipment driven by electric motors (76). These later energy uses are of course included in our dataset, but natural ice is not.

We make here a preliminary attempt here to quantify the role of natural ice in the energy economy. Ice sales were not counted in the Census, and data are scarce: of all the energy sources in the United States, ice is perhaps the most difficult to get firm estimates for. Primary sources record the tonnage of ice taken from individual locations – specific rivers like the Kennebec or Hudson – and the distribution of ice at certain shipping hubs and on international routes, but much of U.S. ice harvesting happened on small ponds and lakes with no record-keeping whatsoever. Prior historical work allows us to make at least a rough estimate. The historian Richard Cummings in a 1949 study estimated per capita U.S. usage of natural ice in 1880 as slightly less than 0.25 tonnes per capita per year (75). Taking this conservatively as entirely natural ice, and multiplying by the latent heat of fusion (the energy required to melt solid ice, 334 kJ/kg), gives an estimate of 2.4 W/cap. for the embodied energy of natural ice use. This value is small relative to the energy economy as a whole, but still is roughly equivalent to all U.S. windpower in 1900, or half of all mechanical water-power, or all electricity used in factories at the time. Another, larger estimate of natural ice was produced by J. C. Jones (77), of 25 million tons in 1886, or roughly 0.44 tonnes per capita per year (4.3 W/cap.).

While the embodied energy of natural ice is not insignificant relative to other sources we include in our dataset, even less information exists about the breakdown of natural ice use by sector, i.e. its industrial vs. commercial vs. household use. Further research might allow estimating this breakdown by examining receipts of ice sales to domestic users and comparing these to total usage. The lack of sectoral detail means that for now, we omit natural ice from our dataset and Sankey diagrams.

6. Definitions

6.1. Sectors. The EIA gives the following definitions of end-use sectors and their activities (78). We seek to maintain similar divisions over time, though with some modifications.

“Residential sector: An energy-consuming sector that consists of living quarters for private households. Common uses of energy associated with this sector include space heating, water heating, air conditioning, and lighting, refrigeration, cooking, and running a variety of other appliances. The residential sector excludes institutional living quarters.”

“Commercial sector: An energy-consuming sector that consists of service-providing facilities and equipment of: businesses; federal, state, and local governments; and other private and public organizations, such as religious, social, or fraternal groups. The commercial sector includes institutional living quarters. It also includes sewage treatment facilities. Common uses of energy associated with this sector include space heating, water heating, air conditioning, lighting, refrigeration, cooking, and running a wide variety of other equipment. Note: This sector includes generators that produce electricity and/or useful thermal output primarily to support the activities of the above-mentioned commercial establishments.”

“Industrial sector: An energy-consuming sector that consists of all facilities and equipment used for producing, processing, or assembling goods. The industrial sector encompasses the following types of activity: manufacturing (NAICS codes 31-33); agriculture, forestry, fishing and hunting (NAICS code 11); mining, including oil and gas extraction (NAICS code 21); and construction (NAICS code 23). Overall energy use in this sector is largely for process heat and cooling and powering machinery, with lesser amounts used for facility heating, air conditioning, and lighting. Fossil fuels are also used as raw material inputs to manufactured products. Note: This sector includes generators that produce electricity and/or useful thermal output primarily to support the above-mentioned industrial activities.”

“Transportation sector: An energy-consuming sector that consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another. Included are automobiles; trucks; buses; motorcycles; trains, subways, and other rail vehicles; aircraft; and ships, barges, and other waterborne vehicles. Vehicles whose primary purpose is not transportation (e.g., construction cranes and bulldozers, farming vehicles, and warehouse tractors and forklifts) are classified in the sector of their primary use.”

“Electric power sector: An energy-consuming sector that consists of electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public – i.e., North American Industry Classification System 22 plants.”

In this work, we count agricultural and industrial use separately, treating agriculture as an industry of particular interest. We define agricultural use as specifically **on-field use,** which excludes the manufacture of inputs and the transport and processing of goods. (We do include some consideration of embodied energy in fertilizer inputs in Section 3.2 here.) We do not attempt to estimate total energy in the food system, since food processing has moved from home to industry over time and would be difficult to disentangle. On the other hand, we combine residential/commercial into a single sector, since they are combined in most estimates of fuel consumption through the early 20th century (as “domestic deliveries” of various fuels). Reliable estimates for disaggregating these subsectors exist from 1949 onward. We present a rough attempt at disaggregating them before 1949 in section 3.1.1, but the subject calls for further research.

While we sometimes show electricity as an input into the other sectors, we always show not the direct use of electricity but the *total primary energy used to generate that electricity.* This accounting is contrary to the convention of the LLNL energy diagrams (7). It is impossible however to correctly assess the relative energy uses of individual sectors if sectors using electricity are not “charged” for the waste heat of generation. In LLNL, transportation appears to be the largest energy-using sector in 2019; in our dataset with full accounting of waste heat, the largest is residential/commercial. Failing to account for this waste heat would also produce distorted historical perspectives. Early on-site steam engines would be assigned their full primary energy use inclusive of thermodynamic inefficiencies, but later electric motors driven by steam turbines would not.

In several cases definitions are problematic and could be refined in the future. We assign electricity for streetlights to transportation, but its designation by the EIA is ambiguous. We assign all asphalt to industry, even though it is mostly used to construct roadways. We count energy used in military vehicles as transportation, which produces a significant increase during WWII. We assign all energy inputs for manufactured gas (primarily coal) to industry, rather than tracking its use in individual sectors (including residential/commercial for household lighting and transportation for municipal lighting). Finally, we are inconsistent in our treatment of wastage: we allocate line losses and waste heat in electricity generation proportionally to all sectors by their electricity use, but assign all wasted oil and refinery losses to industry.

6.2. Fuels.

6.2.1. Biomass. *"On the hoof" transportation:* For a part of the 19th century (∼1860–1890), before the extension of the railroads across the continent, cowhands drove cattle across the prairie and Great Plains to the westernmost railheads. In effect, cattle provided their own transportation for part of the route to slaughterhouses. Their energy expenditures could plausibly be argued to be biomass energy devoted to transportation, or potentially as on-field agricultural use, but we do not count them towards either category. Our calculations exclude the food calories produced by agriculture, and we book-keep only on-field applications of *additional* primary energy. While the energy expended by cattle in traveling does not reach consumers, neither does the bulk of energy absorbed by livestock or crops that are later eaten. We therefore consider the cattle’s energy expenditure to be part of this intrinsic “production energy”, the metabolic needs of the living creatures we later eat.

6.2.2. Electricity Generation from Renewables. Electricity generation from renewables presents a problem in book-keeping, in that it is not obvious how to define their associated flow of primary energy. Primary energy flows are simple to define for *combustion power plants* (those that burn fuels like coal, natural gas, oil, or biomass) as energy content of the primary fuels. The electricity output of these plants is less than these primary inputs, since heat engines are necessarily inefficient at converting heat to work and much of the input energy is lost as waste heat. We always separately track the electricity produced, allowing a simple determination of power plant efficiency. (In some cases where records are scarce, we use an assumed efficiency to reconstruct fuel inputs.) For thermal power plants using *non-combustion heat sources* – nuclear and geothermal – we do not measure the primary energy inputs, but we can assume an efficiency for their turbogenerators. These plants use the same steam turbines as in coal plants, whose efficiencies have been quantified.

For *non-thermal generation* such as wind, hydroelectricity, or solar photovoltaics, defining a an efficiency and therefore a primary energy flow is more complicated. A hydropower turbine has a mechanical efficiency of over 90% — over 90% of the potential energy in water that enters the turbine is converted to mechanical work – but much of a river's flow is typically not used. Should undiverted water be treated as "waste"? Similarly, a wind turbine has an upper limit to the fraction of the kinetic energy of wind it can capture (59.3%, by Betz's Law), since airflow cannot be completely stopped, but it would be strange to consider that undisrupted flow as "waste". While we can measure the electricity produced by non-thermal renewables, defining the primary energy associated with that production is somewhat arbitrary.

The EIA makes a different choice, and assigns electricity from hydro, wind, and solar PV an artificial efficiency equal to that of aggregate generation from all thermal sources (78). This convention has the virtue of making the primary energy assigned to non-thermal renewables vs. fossil sources roughly the same proportions as their electricity production. For a long historical study, however, the convention becomes strange as it would require assuming that the efficiency of non-thermal renewables changes substantially over time. In the 140-year history of the U.S. electric sector, aggregate thermal generation efficiencies have risen from about 2.5% to over 40% (Figure S12). In EIA tables, changing efficiency assumptions produce a misleading apparent decline over time in primary energy from hydroelectricity. U.S. dams and hydroelectric generation have been stable for decades, but the rising efficiency of fossil generation means that hydropower is scaled by a smaller number over time and appears to be shrinking.

In this work we opt for simplicity and consistency across time, and assign non-thermal renewables an efficiency of 1. The choice means that care must be taken in interpreting their primary energy flows, which are undervalued relative to those of energy sources used in thermal generation. In 1890, for example, the electricity generated by hydropower and coal are nearly equal, but coal's primary energy inputs were greater by a factor of 30.

6.3. Physical Assumptions.

Most of our energy flow calculations require some assumption of energy density – energy content per unit mass or per unit volume. Table S2 shows values used in this work, and the sources they are drawn from.

Table S2. Estimated energy content for fuels used throughout this work. Fuel consumption is typically noted in primary sources by volume or by mass; we use these conversion factors to convert to energy units. Values in MJ/kg are provided for only for reference. Fuels marked with an asterisk (*) are discussed further in the text.

Fuel	Energy Content	MJ/kg	Source
Fuel Wood*	21 M BTU/cord	-	Kuhns and Schmidt (2020) (79)
Bituminous Coal*	21 M BTU/ton	24	Schurr and Netschert (1960) (5)
Anthracite Coal*	24 M BTU/ton	28	Schurr and Netschert (1960) (5)
Natural Gas*	1037 BTU/ft.^{3}	48	EIA (2020) (78)
Kerosene	135 K BTU/gal.	47	Engineering Tool Box (2005) (80)
Fuel Oil	135 K BTU/gal.	47	Engineering Tool Box (2005) (80)
Gasoline	124 K BTU/gal.	46	Engineering Tool Box (2005) (80)
Diesel	129.5 K BTU/gal.	41	Engineering Tool Box (2005) (80)
Other Petroleum Products*	135 K BTU/gal.	-	Engineering Tool Box (2005) (80)
Maize ("Corn")	1566 Cal./lb.	14	Wood, Jackson, and Baker (1988) (81)
Oats	3.891 Cal./g	16	Brown, et al. 1963 (82)
Hay	800 Cal./lb.	7	Brown, et al. 1963 (82)
Silage	650 Cal./lb.	6	Brown, et al. 1963 (82)

The energy content of fuelwood can range widely depending on the species. Hardwoods tend to be denser than softwoods, and energy densities by volume range from 13 to 33 million BTU/cord. The typical units of fuelwood, a "cord" (128 ft.^{3} of stacked wood), is also imprecise and includes the air in the stack. We use 21M BTU/cord as a representative figure, as historical American fuel wood use did not tend towards either hard or soft woods.

Anthracite and bituminous coal range widely in their energy density by mass, depending on the seam, mine, and general geology. Our estimate for the energy of each coal type is taken from Schurr and Netschert. Natural gas has a considerably narrower range of possible energy content values. We use the EIA 2019 value for energy content by volume.

"Other Petroleum Products" is a catchall term for distillate products other than the four that we track, and includes some crude oil at 138 K BTU/gal. We ultimately assign "other" products the same energy density as fuel oil.

7. Notes on Estimates

This section provides detailed notes on sources and calculations for individual energy flows. Table S3 below, groups information by four different time periods: 1800–1850, 1850–1900, 1900–1949, and 1949–2019. The earliest period saw the beginnings of coal use and the introduction of steamboats and locomotives. The second period saw momentous changes and a tremendous expansion of energy use. Steelmaking boomed, powered by coal. Railroads converted to coal, and sailing ships were gradually replaced by steamships. The first oil and natural gas wells were drilled, and the first electricity production occurred, using both hydropower and coal-fired thermal generation. The third period saw the rise of petroleum, partially replacing coal for steam engines and powering internal combustion engines in automobiles. The last period saw the expansion of natural gas and the introduction of nuclear power and solar electricity. In the earliest periods, many values must be estimated by proxy; these could be refined in future research. From 1949 onwards, fine-grained data are available from the EIA and little archival research is needed. The most challenging estimations involve disaggregating 19th-century use of combustion fuels (bituminous and anthracite coal and wood); Section 7.1 summarizes our approach. Sections 7.2–7.14 provide details on individual estimates.

Table S3. Summary of estimates in four periods, from top to bottom: 1800–1850, 1850–1900, 1900–1949, and 1949–2019. Each cell corresponds to the flow of energy from a primary source (left) to a use (top), with electricity included in both categories. References in cells give relevant sub-sections. Rightmost column lists sources used in determining each flow. *Color coding:* Cell colored denotes uncertainty: red cells are estimated from non-energy proxies; yellow cells are extrapolated or interpolated in part or taken from a secondary source; green cells are fully known to a high degree of confidence. "Total" column shows certainty of fuel totals (the sum of individual fuel streams).

Fuel	Elect.	Res./Com.	Ag.	Indust.	Trans.	Total	Sources
Water	-	-	-	7.8	-	-	(1, 5, 6, 20)
Wind	-	-	-	-	7.9	-	(5, 6)
Coal	-	7.1	-	7.2	7.3, 7.4	-	(1, 2, 4–6, 13, 29, 35, 48, 49, 55, 83–106)
Biomass	-	7.5, 7.7	7.6	7.2, 7.5	7.3, 7.4, 7.5, 7.6	-	(1–6, 9, 12, 18, 28, 37, 48, 49, 70, 83–97, 99, 100, 102, 107–126)
Water	7.12	-	-	7.8	-	-	(1, 5, 30, 40, 127–129)
Wind	-	-	7.9	-	7.9	-	(6, 31, 130)
Natural Gas	7.10, 7.12	7.10	-	7.2, 7.10	7.10	-	(2, 5, 95, 131–133)
Coal	7.12	7.1	-	7.2	7.3, 7.4	-	(1, 2, 4–6, 13, 29, 35, 48, 49, 55, 83–106)
Biomass	-	7.5, 7.7	7.6	7.2, 7.5	7.3, 7.4, 7.5	-	(1–6, 9, 12, 18, 28, 37, 48, 49, 70, 83–97, 99, 100, 102, 107–126)
Petroleum	7.11, 7.12	7.11	-	7.2, 7.11	7.11	-	(1–3, 5, 6, 28–30, 37, 40, 55, 83, 84, 97–101, 103–106, 127, 128)
Electricity	-	-	-	7.12	7.12	-	(1, 2, 5, 6, 30–32, 40, 127–130, 134–136)
Water	7.12	-	-	7.8	-	-	(1, 5, 30, 40, 127–129)
Wind	7.12	-	7.9	-	7.9	-	(6, 31, 130)
Natural Gas	7.10	7.10	-	7.10	7.10	-	(2, 5, 95, 131–133)
Coal	7.12	7.1	-	7.2	7.3, 7.4	-	(1, 2, 4–6, 13, 29, 30, 35, 40, 48, 49, 55, 83–106, 127–129, 134–136)
Biomass	-	7.5	7.6	7.2, 7.5	7.3, 7.4, 7.6	-	(1–6, 9, 12, 18, 28, 37, 48, 49, 70, 83–97, 99, 100, 102, 107–126)
Petroleum	7.11, 7.12	7.11	7.11	7.11	7.11	-	(1–3, 5, 6, 28–30, 37, 40, 41, 55, 56, 83, 84, 97–101, 103–106, 127, 128)
Electricity	-	7.12	7.12	7.12	7.12	-	(1, 2, 5, 6, 30–32, 40, 127–130, 134–136)
Solar	7.13	-	-	-	-	-	(2)
Nuclear	7.13	-	-	-	-	-	(2)
Water	7.13	-	-	-	-	-	(2)
Wind	7.12, 7.13	-	7.9	-	7.9	-	(2, 6, 31, 130)
Geothermal	7.13	7.13	-	7.13	-	-	(2)
Natural Gas	7.13	7.13	7.13	7.13	7.13	-	(2, 3, 41, 137, 138)
Coal	7.13	7.13	-	7.13	7.13	-	(2)
Biomass	7.13	7.13	7.13	7.13	7.13	-	(2, 5)
Petroleum	7.13	7.13	7.13	7.13	7.13	-	(2, 3, 41, 137, 138)
Electricity	-	7.13	7.13	7.13	7.13	-	(2, 3, 6, 41, 137, 138)

7.1. Summary: disaggregating early uses of coal, wood, and petroleum.

For *coal*, the Historical Statistics of the United States (HSUS) reports annual total production of bituminous and anthracite from 1800 (6).[7] We have full information on end-uses of coal from 1949 from the EIA, and from 1935 from detailed studies by Schurr and Netschert (5). For prior years, we generally estimate transportation and industrial coal use using proxies, and assign the remainder of coal production to the residential/commercial sector. This domestic consumption is the bulk of U.S. coal usage in the early 19th century, with household coal use split between clean-burning anthracite and lower-grade bituminous coal. Industrial and transportation estimations are described below. For a few individual years – 1910, 1915, 1920, and 1923 – we have detailed sectoral coal usage, including residential, from government reports (1, 84). For these years we need not assign residential usage by subtraction, but instead must adjust recorded numbers to match production totals. Adjustments are typically around 10% and do not exceed 15%; the same adjustment factor is applied to each sector.[8]

For *wood*, total production was not tracked by the HSUS. Most domestic firewood was simply harvested by rural families, and even marketed fuel-wood and charcoal were produced by small-scale operators. The first government estimates of wood consumption occur in a report in the 1880 Census (1), and wood use is regularly reported only after 1920. (4). However, the vast majority of early U.S. wood consumption occurred in households for heating, and this use has been extensively studied by historians from contemporary letters and other primary sources. We use the estimates of Schurr and Netschert (5) between 1850–1945. Per capita wood use falls over this period, reflecting among other things the substitution of coal. For all years before 1850, we assign residential wood usage the 1850 value from (5) of 4.5 cords/year/person. Because pre-1850 coal usage is small, and wood estimates are rough, we do not attempt to adjust wood usage to account for the early evolution of domestic coal use. (In 1800, only ∼0.5% of residential heating was supplied by coal in our estimates; the proportion rises to 10% in 1850 when the Schurr and Netschert estimates begin.) Our resulting residential wood timeseries is broadly consistent with estimates by other historians (32, 124) and if anything may be conservative. Wood usage outside the home was comparatively small – transportation, i.e. railroads and steamboats, accounts for <1% of total wood use and industry 4–8% before 1910 – but is important for understanding energy transitions within these sectors. Wood use in transportation and industry must be estimated in combination with other fuels, to apportion energy consumption between wood, bituminous, anthracite, and in some cases petroleum. For overall wood use, see Figure S19.

For *petroleum*, production records begin immediately after the drilling of the first U.S. oil well in 1859. The EIA reports total crude oil production from 1860 (2), and Schurr and Netschert record the refining of various petroleum distillates from 1875 (5). Records of sectoral uses of petroleum products begin with the 1925 Census (1), which tracks use of fuel oil, kerosene, gasoline, and diesel in approximately 20 sub-sectors; these are aggregated by Schurr and Netschert (5). For pre-1925 years, we allocate petroleum products to sectors based on proxy data, or holding constant 1925 shares, except when these values are known to have changed significantly. In these cases we allocate proportions to sectors based on secondary sources (29, 55, 97, 101). Figure S20 summarizes the resulting sub-sectoral petroleum use from 1800–1955.

Assigning fuels in transportation. Railroads, river steamboats, and ocean-going steamships were all first powered by external-combustion steam engines. Railroads and steamboats began as purely wood-powered and transitioned to coal during the 19th century, with railroads also making some use of petroleum in the form of fuel oil. Steamships began as coal-powered, but largely converted to fuel oil in the early 20th century. To estimate their consumption of individual fuels, we combine estimates of total fuel use and of evolving fuel shares.

Assigning fuels in industry. Energy use in industry is more complicated than that in transportation as it involves both process heat and motive power, and manufacturing processes for different products may have very different requirements and timelines for energy transitions. We construct individual estimates of fuel usage in four commodities – iron and steel, brick and tile, glass, and cement – that substantially contributed to industrial energy use in the 19th century. When detailed records begin in 1910, these four sub-sectors made up 45% of industrial non-electric energy use (and 52% of bituminous coal, the primary industrial energy source at the time). In some cases we have primary-source records of volume of manufactured output made with individual fuels (for example, the annual tons of pig iron produced with wood charcoal). In other cases we estimate the evolving proportions of individual fuels.

We estimate industrial energy use outside the four index commodities differently for individual fuels. For anthracite, the earliest fossil fuel used in the U.S. (90), we assume *no* use outside the four index commodities from 1800–1860. After 1860 anthracite was used in new, specialized contexts, including coal gas and petroleum refining. We therefore interpolate absolute usage linearly between 1860–1910. For bituminous, we assume that usage began in 1850 and derive total usage in 1850–1910 by scaling up our index-commodity values by the 1910 factor (1/0.52 or 1.92).[9] For wood, we make use of an additional data point: the 1880 Report on Manufacturers (1) provided a detailed survey of industrial wood use, showing 26% of wood used outside our index industries. We therefore scale up wood in our index commodities by ×1.26 for the years 1800–1880. (Note that none of these scaling factors involve electricity generation, which we treat separately from the remainder of industry.)

The resulting sub-sectoral evolution of fuel use from 1800–1945 is summarized in tables and figures below. Table S4 and Figure S18 show sub-sectoral coal use; Table S5 and Figure S19 show fuel wood use; and Table S6 and Figure S20 show use of petroleum products. In the detailed discussion of industry in Section 7.2, Table S7 shows industrial use of coal and wood from 1800–1910.

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[7] We do not have information on changes in coal stocks, so our consumption timeseries may exhibit excess variability in volatile periods when customers were stockpiling.

[8] We also adjust the years 1935–1945, when aggregated values from Schurr and Netschert (5) underestimate recorded total coal production by ∼10%.

[9] This procedure may slightly overestimate early industrial coal use: U.S. textile manufacturing used coal-powered steam engines in 1910, but in 1850 still involved substantial use of water wheels.

Table S4. Coal, all sectors, 1800–1945. This table summarizes our final estimates constructed as described in the text. All values are given in thousands of tons of coal. Note that bituminous and anthracite coal have different energy content at 24MBTU and 25MBTU, respectively; see section 6.3. Bolded values are reported directly in primary sources and unbolded are estimated by proxy.

Year	total bitum.	total anth.	res./c. total	ind. total	transp. total	elec. total	res./c. bitum.	ind. bitum.	transp. bitum.	elec. bitum.	res./c. anth.	ind. anth.	transp. anth.	elec. anth.
1800	**108**	**0**	108	0	0	0	108	-	-	-	-	-	-	-
1810	**176**	**2**	176	1	1	0	175	-	1	-	1	-	-	-
1820	**330**	**4**	311	1	22	0	308	-	22	-	3	1	-	-
1830	**646**	**235**	806	2	73	0	573	-	73	-	233	2	-	-
1840	**1345**	**1129**	1891	311	272	0	1073	-	272	-	818	311	-	-
1850	**4029**	**4327**	5668	1811	877	0	2495	661	873	-	3173	1150	3	-
1860	**9057**	**10984**	12768	5594	1679	0	4187	3202	1669	-	8581	2393	10	-
1870	**20800**	**19800**	20426	14754	5420	0	6785	8653	5361	-	13641	6101	59	-
1880	**50757**	**28650**	30698	28531	20178	0	10388	20536	19833	-	20310	7995	345	-
1885	**68600**	**37700**	42389	38089	25821	18	15304	27756	25541	-	27085	10334	280	1
1890	**111302**	**46469**	63360	62414	31960	37	30163	49742	**31362**	35	33197	12673	598	2
1900	**212316**	**57368**	101486	105496	61509	1193	57463	93427	**60305**	1121	44024	12068	1204	72
1905	**290500**	**75200**	130595	139958	92543	2604	70658	126754	**90716**	2372	59938	13204	1827	232
1910	**417111**	**84465**	126663	193511	121116	4323	**59628**	**179172**	**118726**	3623	67036	**14339**	2390	700
1915	**408800**	87976	143615	198349	135363	13333	**74807**	**184193**	**132724**	10960	68808	14157	2639	2373
1920	**508595**	**89598**	163160	238094	146785	39695	**92580**	**224120**	**144312**	**37124**	70580	13974	**2473**	2571
1923	**519000**	76404	151884	260600	132820	39866	**93603**	**247897**	**130141**	**37124**	58281	12703	**2679**	2742
1925	**499193**	**61817**	137274	249868	131669	42199	91292	238437	**129242**	**40222**	45982	**11431**	2427	1977
1927	**499801**	61892	139358	250172	129913	42250	93320	238727	**127483**	40271	46038	11445	2430	1979
1928	**498828**	61772	142680	249685	126067	42168	96732	238262	**123641**	40193	45948	11423	2426	1976
1929	**519555**	64339	151897	260060	128017	43920	104039	248162	**125491**	41863	47857	11897	2526	2058
1930	**454990**	**69385**	143509	226211	109692	44962	87289	217323	**107480**	**42898**	56221	8888	2212	2064
1931	**371869**	65728	117430	185765	91961	42441	63898	177621	**89845**	40506	53532	8144	2116	1936
1935	**356326**	**51100**	123220	116689	84643	32359	**80444**	**111521**	**82910**	**30936**	42776	5168	1733	**1423**
1940	**430910**	**49000**	123987	131036	91377	74601	**84687**	**125337**	**90374**	**71603**	**39300**	**5699**	1003	**2998**
1945	**559567**	**51600**	158197	148872	132998	92410	**119297**	**142871**	**130447**	**88262**	**38900**	6001	2551	**4148**

Table S5. Fuel wood, all sectors, 1800–1945. This table summarizes our final estimates constructed as described in the text. All values given in cords/year. For industry, we show only the two largest sub-sectors of the four we estimate, omitting glassmaking and cement. For full industrial estimates see Tables S7–S11. Bolded values are reported directly in primary sources and unbolded are estimated by proxy.

year	total	res./comm.	industrial	*iron and steel*	*brickmaking*	transport.	*railroads*	*steamboats*
1800	23895000	22910848	984152	408543	278269	-	-	-
1810	32580000	30914982	1661772	832217	379553	3246	-	3246
1820	43380000	41806919	1503902	302624	505267	69179	-	69179
1830	57870000	53498756	4185067	2542045	674493	186178	972	185206
1840	76500000	70332668	5631040	3534654	894833	536292	119035	417257
1850	102000000	93857260	6934901	4327530	1215828	1207838	517984	689854
1860	126000000	119013986	4744560	2145305	1318706	2241454	1462806	778648
1870	138000000	125840907	7984373	5820572	1010691	4174720	3350221	824499
1880	**147300000**	**140537000**	**4220802**	1739802	**1157522**	**2766775**	**1972000**	**794775**
1890	120000000	114614142	3951074	1862480	871721	1434784	640009	794775
1900	100000000	88686261	11020034	1739803	811080	293705	136598	157108
1910	91000000	85210958	**5481311**	**235000**	**1069973**	307731	275258	32473
1915	87000000	79279021	7637474			83505	83505	0
1920	83000000	73097085	9793637			**109278**	**109278**	
1925	79000000	66929582	11949799			**120619**	**120619**	
1930	75000000	60894038	14105962			0	0	
1935	72000000	55737875	16262125					
1940	70000000	51581712	18418288					
1945	65000000	44425549	20574451					
1949	**73498361**	**51198980**	**22299381**					

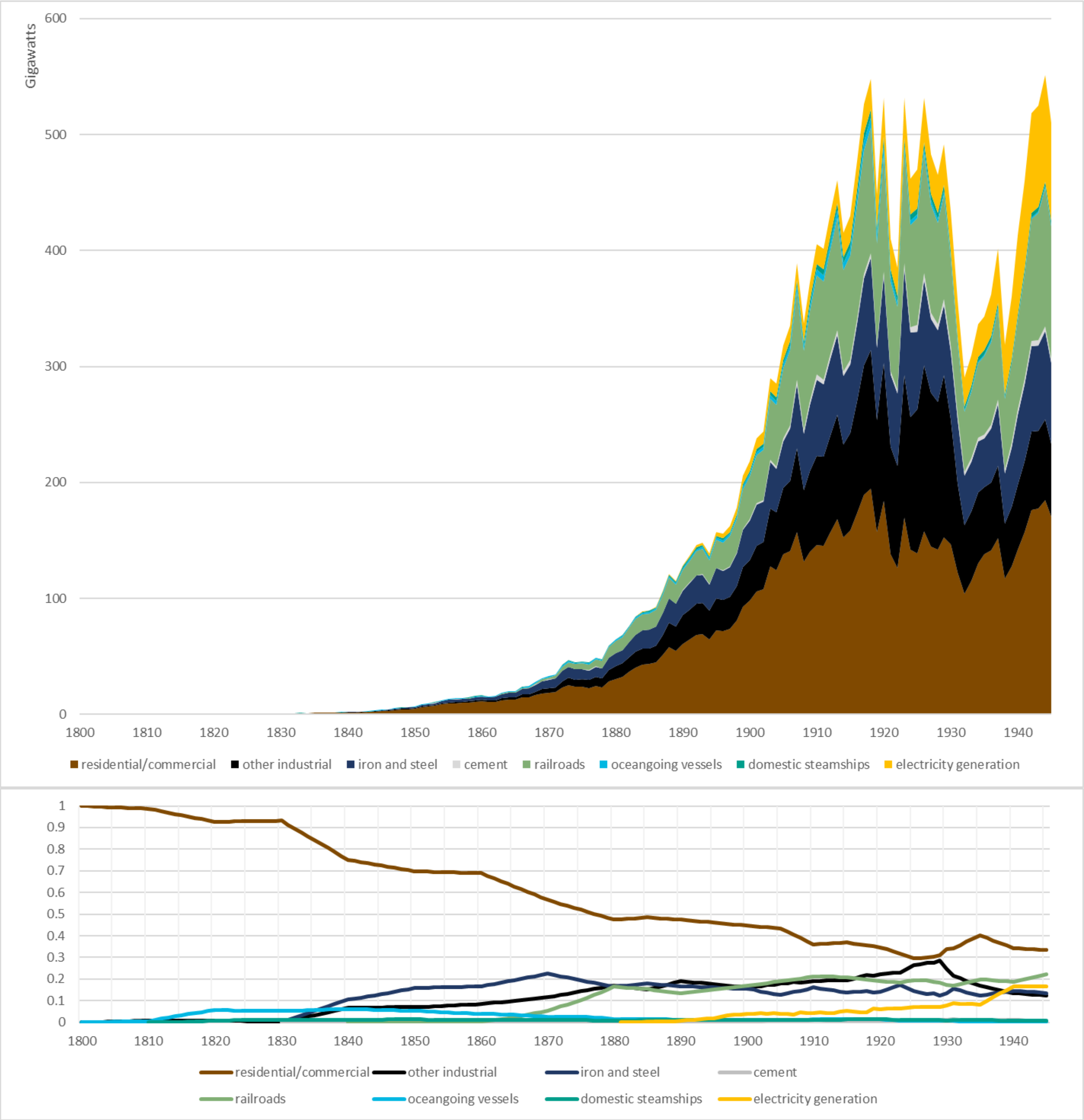

Fig. S18. Coal usage disaggregated by sub-sector, 1800–1945, as total usage (top) and sub-sectoral share (bottom). For detailed discussion of individual estimates, see especially Sections 7.2–7.4. Values shown are absolute power usage in GW, taken from Tables S4 and S7 with values originally stated in tons coal converted using the assumed energy densities for bituminous and anthracite listed in Table S2. The timeseries is annualized by scaling intervening years based on HSUS annual coal production. This process may introduce spurious "noise" when annual production fluctuates strongly, as in the 1910s, since we do not have sufficient information to attribute those fluctuations to individual sectors. Our timeseries also does not account for potential stockpiling of coal during volatile periods. Note that the Great Depression of the 1930s affects industrial coal use most strongly and residential usage the least. This figure disaggregates industry into several sub-sectors; coal use of the entire industrial sector surpassed residential/commercial in 1910.

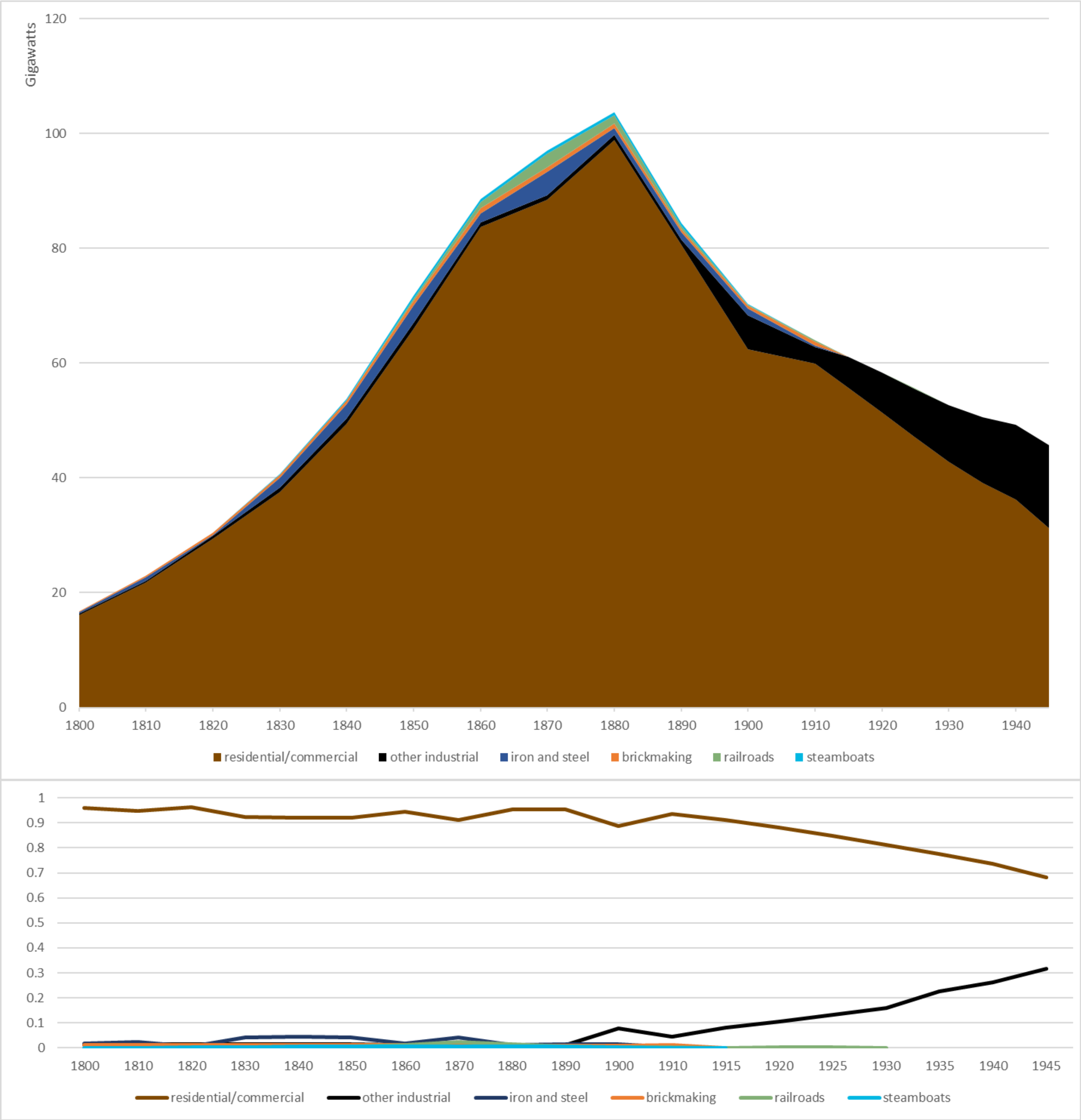

Fig. S19. Fuel wood usage disaggregated by sub-sector, 1800–1945, as total usage (top) and sub-sectoral share (bottom). For detailed discussion of individual estimates, see Sections Sections 7.2–7.4 and 7.5. Values shown are absolute power usage in GW, taken from Table S5. Values originally stated in cords are converted using the assumed energy densities listed in Table S2. Values are decadal only as we do not have annual fuel wood production statistics. Wood was the largest since primary energy source in the U.S. until the 1880s, when it was surpassed by coal. Industrial wood use rises over 6-fold from 1890 to 1945, likely because of the growing paper industry.

Table S6. Petroleum and its products, 1860–1945. Bolded values are reported directly in primary sources (6) and unbolded values are interpolated linearly between known values, or proportions are held constant where no data exists. Fuel totals are given in thousands of barrels, and sectoral totals in GW for consistency, since distillate products have different energy densities. For construction of this petroleum consumption timeseries, see Section 7.11 and Figure S25. Kerosene and gasoline usage before 1875 is estimated by holding their share of total petroleum constant at 1875 values. Before 1900, all kerosene use is assigned to residential/commercial and all gasoline and fuel oil use to industry. (Fuel oil is also termed "distillate" in government statistics.) For allocation to individual sectors after 1900, see Section 7.11 and Tables S22–S24, which estimate sectoral shares of individual distillate products (5). After summing individual petroleum product categories, we allocate the remainder of oil production to industry. This category includes unrefined crude oil, losses, and products consumed as feedstocks in manufacturing rather than as fuels. The apparent strong drop in petroleum consumption in 1885 is considered an artifact of inconsistent accounting for stocks, i.e. much of booming production in 1880 was likely stockpiled and consumed later (5).

year	total	gasoline	diesel	kerosene	fuel oil	residual	other fin. products	uniden. /losses	res. /com.	ag.	ind.	trans.	elec. gen.
1860	**500**	245	-	177	-	-	-	-	0.034	-	0.067	-	-
1865	**1770**	818	-	591	-	-	-	-	0.11	-	0.22	-	-
1870	**2011**	900	-	650	-	-	-	-	0.12	-	0.25	-	-
1875	**2002**	**900**	-	**650**	-	-	-	-	0.12	-	0.25	-	-
1880	**17203**	**1500**	-	**11000**	**500**	-	-	-	2.1	-	1.1	-	-
1885	**7172**	625	-	4583	208	-	-	-	0.87	-	0.47	-	-
1890	**27652**	**3900**	-	**20200**	**1400**	-	-	-	3.8	-	1.4	-	-
1895	**29726**	4200	-	21754	1508	-	-	-	4.1	-	1.5	-	0.014
1900	**39564**	**6700**	-	**30000**	**7300**	-	-	-	6.0	-	1.5	0.08	0.069
1905	**105119**	**6900**	-	**32400**	**8600**	-	-	-	6.7	-	13.3	0.28	0.082
1910	**173559**	**12900**	-	**39800**	**40500**	-	-	-	8.6	0.003	18.5	5.9	0.77
1915	**243230**	**34800**	-	**46200**	**88800**	-	-	-	11	0.079	19.4	16	1.7
1920	**454242**	**101208**	-	**33082**	**185972**	-	**25064**	**110478**	9.5	0.78	50.7	36	6.1
1925	**716096**	**223865**	-	**39969**	**307004**	-	**52393**	**103751**	13	1.7	64.3	74	6.4
1930	**970762**	**394800**	-	**34736**	**368531**	-	**87404**	**40979**	17	2.9	79.9	110	5.1
1935	**945857**	**434810**	**16174**	**47645**	**69854**	**280695**	**102068**	**32440**	**26**	**3.3**	**52.8**	**113**	**4.5**
1940	**1284954**	**589490**	**24669**	**68776**	**136182**	**340163**	**147391**	**19949**	**46**	**5.0**	**58.7**	**148**	**6.2**
1945	**1661487**	**696333**	**66412**	**75573**	**159672**	**523423**	**229121**	**22151**	**48**	**9.0**	**83.1**	**210**	**7.8**

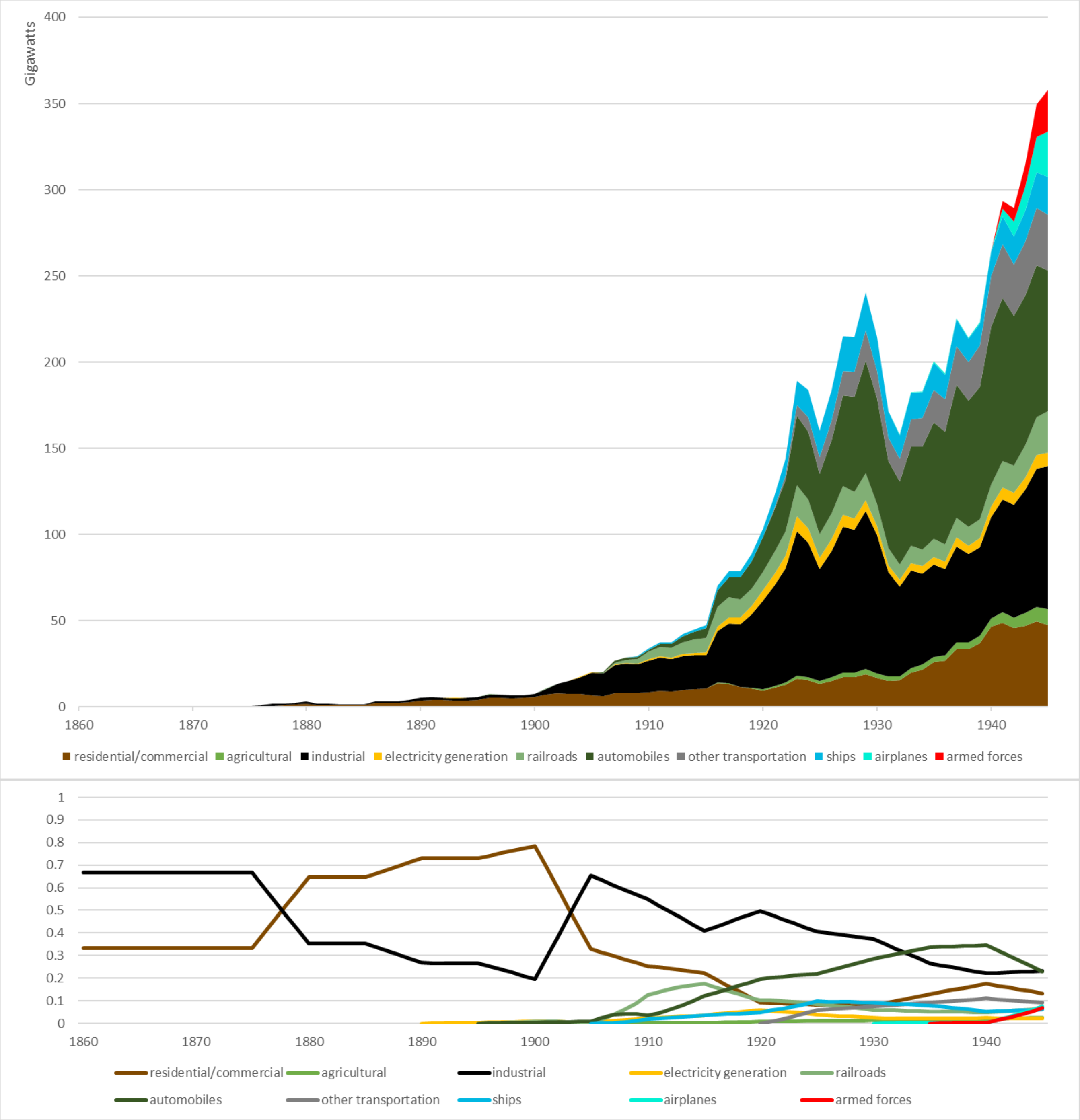

Fig. S20. Petroleum usage disaggregated by sub-sector, 1860–1945, as total usage (top) and sub-sectoral share (bottom). Note that x-axis differs from that of Figures S18 and S19 since petroleum usage begins only in 1859. For detailed discussion of individual estimates, see Section 7.11. Values shown are absolute power usage in GW, taken from Table S6, with distillate volumes converted to common units using the assumed energy densities of Table S2. The timeseries is annualized by scaling intervening years based on our annual timeseries of petroleum consumption. Transportation surpassed industry in sectoral use of petroleum in the mid-1920s, and by the mid-1930s automobiles alone exceeded all industrial petroleum use.

7.2. Industrial combustion fuels, 1800–1910. We estimate early industrial demand for individual fuels by focusing on four major industries, which were important in the American economy across this period and which dominated early industrial energy use. 1) Iron/steel is the largest single user of industrial heat throughout the 19th and early 20th century, and has the most reliable statistics of energy use. In 1910, iron and steel alone accounted for 38% of total industrial combustion energy use. 2) Brick and tile-making was both a very early industry to become established, and used significant amounts of wood later than most other sub-sectors. 3) Glassmaking was an early industry of significant interest as an early adopter of new fuels, using some coal as early as 1810, and adopting natural gas already in the 1880s. 4) Cement manufacture was one of the largest industrial users of energy by the end of the 19th century, and has an extensive statistical record.

We estimate the fuel use of each industry from their industrial output, for which detailed statistics extend quite far back in history. Iron and steel was tracked since 1800, cement since 1820, and bricks since 1870 (6). Glassmaking is the exception, with minimal records, so we estimate fuel consumption via the number of workers or factories. For pre-1870 brickmaking, we assume an equal number of bricks per capita. Key sources of information used in these estimates include 1) the U.S. Geological Survey's periodically issued "Mineral Resources of the United States" reports (83, 84), which surveyed industrial and residential consumers and recorded e.g. fuel usage in railroads or iron and steel, and 2) the decennial Census Report on Manufactures (1) which recorded data on fuel use in manufacturing first for limited industries (e.g. iron and steel) and by 1910 for all industries. We apply evolving fuel shares between types of coal and fuel wood based on secondary research on each industry. From these four index industries, we scale industrial use of coal and wood as described in Section 7.1.

Figure S21 shows the known use of combustion fuels in all industrial sub-sectors in 1910 from the Census *Report on Manufacturers* (1), which comprise the first comprehensive estimate of industrial fuel use in American history. Table S7 shows the final estimates of fuel use each year from 1800–1910 for the index commodities and the entire industrial sector.

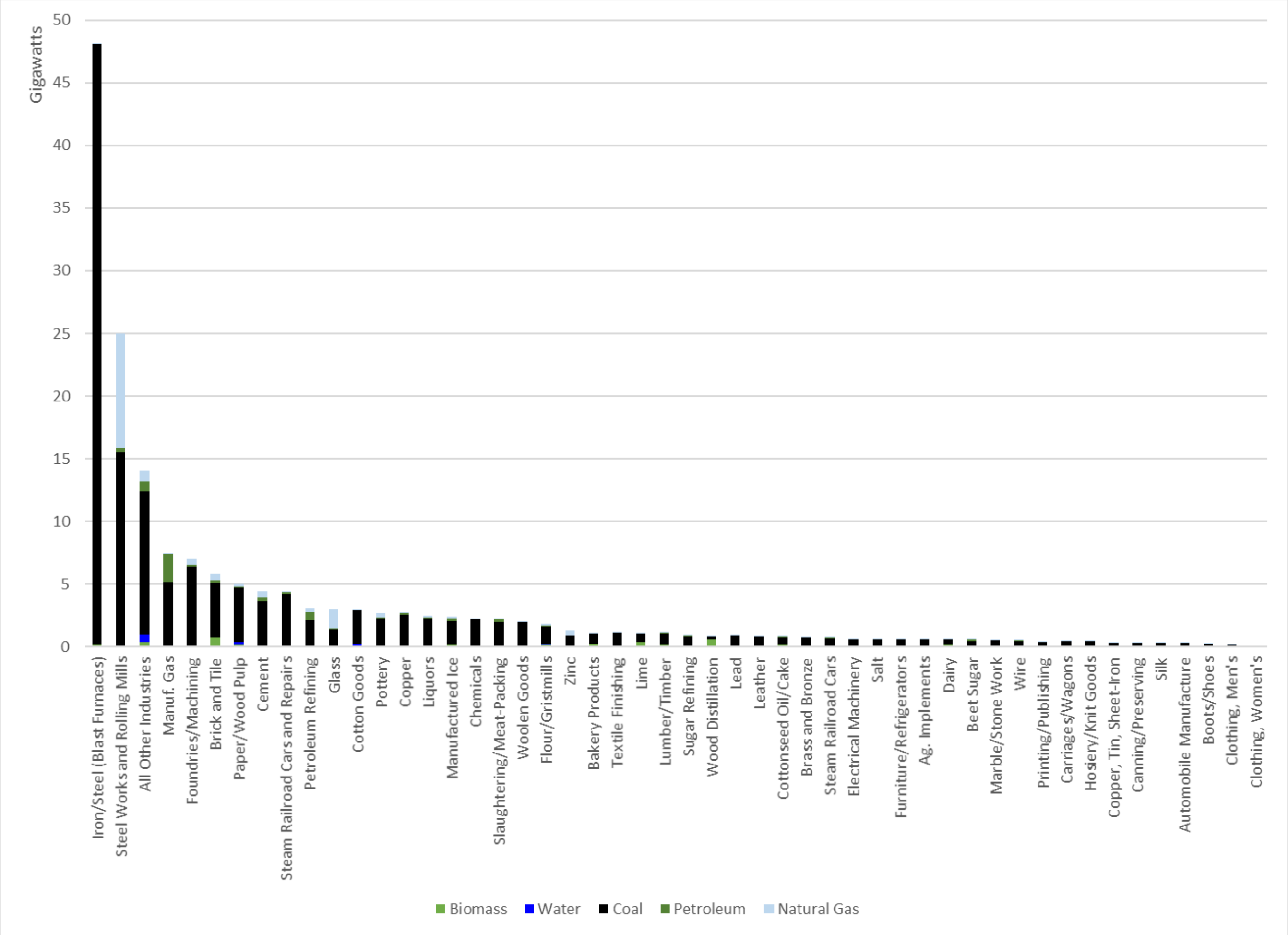

Fig. S21. Estimated energy use by industrial sub-sectors, 1910, from the 1910 Census *Report on Manufactures* (1), which surveyed all manufacturing industries. Note that this figure excludes the small amount of industrial electricity at the time (1.1 GW of electricity made from 5.9 GW of primary energy, or 3% of total industrial energy use). In 1910, iron and steel account for 38% of industrial non-electricity energy use; brick and tile: 2.8%; cement 2.1%; and glass 1.4%; proportions were higher in the 19th century. The detailed 1910 data provide the scaling factors that allow us to estimate early fuel use in our four index industries and in the industrial sector as a whole. Note the early use of natural gas in glassmaking and in steel mills. Most blast furnace fuel at the time is coke made from bituminous coal.

Table S7. Fuels in all industry and in index commodities (iron/steel, brickmaking, glassmaking, and cement), 1800–1910. Values for individual industries are scaled based on their output, or taken directly from the Census Reports on Manufactures, 1880–1910 (1). (See Tables S8–S11 for details.) Bolded values are given directly in primary sources and unbolded values are derived. Total industrial use is derived as described in Section 7.1. Coal values are given in thousands of tons and wood values in thousands of cords. The heat content for a cord of wood and a ton of coal are roughly comparable: we assume 24 and 25M BTU/ton for bituminous and anthracite, respectively, and 21M BTU/cord for wood

year	wood total	wood iron/steel	wood brick	wood glass	wood cem.	bitum. total	bitum. iron/steel	bitum. brick	bitum. glass	bitum. cem.	anth. total	anth. iron/steel	anth. brick	anth. glass	anth. cem.
1800	984	409	278	38	-	-	-	-	-	-	-	-	-	-	-
1810	1662	832	380	77	-	-	-	-	-	-	1	-	-	1	-
1820	1504	303	505	154	2	-	-	-	-	-	1	-	-	1	-
1830	4185	2542	674	223	7	-	-	-	-	-	2	-	-	2	-
1840	5306	3535	895	236	23	-	-	-	-	-	311	254	157	52	5
1850	5830	4328	1216	183	36	661	315	122	7	37	1150	997	426	128	25
1860	3846	2145	1319	93	18	3202	1524	330	36	181	2393	1817	433	240	47
1870	7984	5821	1011	155	25	8653	4153	404	48	301	6101	4930	531	399	64
1880	**4221**	**1740**	**1158**	190	18	20536	**9858**	634	57	613	7995	**3322**	965	575	54
1885						27756					10334				
1890	3951	**993**	872	139	33	49742	**23483**	1738	364	1454	12673	**2974**	2797	403	101
1900	11020	**928**	811	81	28	93427	**40402**	4164	1021	1290	12068	**1831**	355	212	74
1905						126754	**50300**				13204				
1910	**5481**	**235**	**1070**	**12**	**6**	**179172**	**80593**	**5773**	**4816**	**1859**	**14339**	**1030**	**236**	**18**	**259**

7.2.1. Iron and steel. Iron and steel production is the single largest energy-consuming industrial sub-sector in the U.S. throughout the 19th century and in much of the 20th. Heat is needed in multiple stages: first, in smelting iron from its ore, in processing that iron into various grades of steel, and finally in reheating the metal to produce finished goods.

The evolution the U.S. iron and steel industry has been extensively studied by historians. In the early 1800s, U.S. iron was made entirely with charcoal (which burns at a hotter temperature than the wood from which it is made). Charcoal remained the predominant iron-making fuel even after the development of Pennsylvania anthracite mines, for multiple reasons: iron was produced in small operations far from the mines; charcoal iron could be made in simpler furnaces; and charcoal produced a superior iron with fewer impurities (85). U.S. iron production therefore used vast quantities of wood (86, 87). Use of anthracite coal for smelting grew in the 1840s, when railroads could carry ore, coal, or metal products, and industrial-scale hot-blast furnaces began producing cheaper anthracite iron for distant markets (29, 49, 85, 88–90). By the 1870s, half of U.S. iron was produced by anthracite (88).

The use of bituminous, ”soft” coal in ironmaking required its conversion into coke, a nearly pure carbon fuel derived by pyrolysis of coal in an oven or closed chamber. Experiments with coke production in the U.S. started in the 1810s and a successful coke-using blast furnace in the U.S. was established in 1837 (91), but American coke remained high in impurities. Coke use accelerated only in the 1860s-1870s when quality improved (89). Bituminous use in iron and steel surpassed anthracite in the 1880s, and anthracite use actually shrank in absolute terms from the 1890s (88). Coke made from abundant bituminous coal powered the tremendous growth in U.S. steel production enabled by the new Bessemer process, and by 1900, the energy for 90% of all U.S. iron and steel was derived from bituminous coal (1, 88).

Table S8. Fuels in iron and steel production, 1800–1910. Bolded values are given directly in primary sources, and unbolded values are estimated, using a scaling equivalent to 2.8 T coal or coal equivalent for every 1 ton iron/steel produced, derived from the 1880 Report on Manufactures (1), and efficiencies of 0.3 and 0.56 in the production of charcoal and coke, respectively. (See text for discussion.) Coal and metal quantities are given in thousands of tons and wood values in thousands of cords. The heat content for a cord of wood and a ton of coal are roughly comparable: we assume 24 and 25M BTU/ton for bituminous and anthracite, respectively, and 21M BTU/cord for wood.

year	charcoal share	bituminous (incl. coke)	anthracite share	coal share total	pig iron	all other iron/steel	wood	charcoal	bituminous	anthracite	coke
1800	**1.00**	0.00		0.00	**27**	17	409	163	-	-	-
1810	**1.00**	0.00		0.00	**55**	34	832	333	-	-	-
1820	**1.00**	0.00		0.00	**20**	12	303	121	-	-	-
1830	**1.00**	0.00		0.00	**168**	103	2542	1017	-	-	-
1840	0.80	0.00	0.20	0.20	**292**	180	3535	1414	-	254	-
1850	**0.50**	0.10	0.40	0.50	**572**	352	4328	1731	189	997	69
1860	**0.17**	**0.33**	**0.50**	**0.83**	**834**	**513**	2145	858	899	1817	339
1870	**0.17**	**0.33**	**0.50**	**0.83**	**2053**	**1602**	5821	2328	2417	4930	941
1880	**0.13**	0.42	0.45	**0.87**	**2597**	**1672**	1740	**696**	**5659**	**3322**	**2278**
1890	**0.07**	**0.71**	**0.22**	**0.93**	**6308**	**3476**	1862	**745**	**5723**	**2974**	**9632**
1900	0.03	0.90	0.08	0.98			1740	**696**	**11778**	**1831**	**15525**
1910							**235**		**21040**	**1030**	**32300**

To estimate the contribution of different fuels to U.S. iron/steel production, we develop 1) a decennial metric of total production, 2) an estimate of the share of production from each fuel, and 3) scaling factors that relate primary energy used per final iron and steel produced. We estimate total production (1) by adding pig iron production from HSUS (6) to 'other' iron and steel (i.e. not produced via pig iron) taken from the Census Reports on Manufactures, 1860–1910 (1), which reports it from 1860 onwards. For pre-1860 years, we use HSUS pig iron and 1860 proportions, adding $\sim$ 1 ton of 'other' to every 1.6 tons of pig iron. This procedure may overstate the metal production in early years, as 1860 values already include some Bessemer steel. We estimate shares of iron produced by each fuel (2) using data from government reports (the Census Report on Manufacturers for 1854 and 1880 (1)), from contemporaneous sources reporting e.g. volumes of charcoal vs. anthracite iron (86, 88), and from historical studies (85, 87, 92). For years where we have no reported fuel shares, we interpolate.

We assume a scaling from primary fuel sources to final volume of metal output (3) using the detailed statistics of the 1880 Census Report on Manufacturers (1), whose reported energy use in all iron and steelmaking is the equivalent of 2.8 tons bituminous coal per ton metal produced. (This measure excludes the inefficiencies in producing charcoal from wood or coke form coal; these are accounted for later.) This value is approximately 2 times higher than the reported estimates of energy use in smelting alone because it includes energy use throughout all stages of working the metal, including refining, rolling, slitting, etc. By contrast, collected contemporary estimates of fuel needed for smelting range from 0.5 to 2 tons coal equivalent per ton pig iron for charcoal production (87, 93); and 1.25–1.85 tons for coke (88, 91). We then apply additional factors to account for energy losses in producing charcoal from wood (0.3, reported consistently by (87) and (93)) and in producing coke from bituminous coal (0.56, from reported values for coke production in the 1880 Report on Manufactures (1); this number includes both a mass conversion of 1.84 tons coal to 1 ton coke, and the slightly higher energy density of coke.)

7.2.2. Brick and tile. Brickmaking, one of the oldest industries in the United States, has been considerably less well-studied than iron and steel. Brick and tile manufacture is known to be distinctive in remaining heavily dependent on wood even when other sectors had converted. Brickmaking, like early iron, occurred in dispersed rural locations and relied on local fuel wood; it also only barely saw mechanization in the late 1860s, and did not mechanize fully until the 1880s (94). Brickmaking used substantial fuel wood throughout the 19th century. In 1850, fuel wood made up the only input for brick manufacturers in Lancaster, PA, in a survey by that year's Census (1). The 1880 "Forest Census" listed bricks as one of the chief users of fuel wood (alongside households, railroads, steamboats, and salt), and the 1910 Census Report on Manufactures noted that bricks remained the the biggest single non-domestic user of wood energy (1). Brick and tile appear to have begun the transition to coal about three decades later than did iron. We construct a timeseries of evolving wood share from an assumed 100% in 1850 to reported values of 42% in 1880 and 15% in 1910.

We assume for lack of information that the energy used in early brick manufacture remained constant at its earliest reported value (in 1910) (1), roughly 0.58 Watts per brick per year or $\sim$18 MJ/brick. Where even brick statistics are unavailable (before 1870), we also assume that the number of bricks produced per year remained constant per capita at 1870 values (72.5 bricks/person/year). Results are shown in Table S9. Early estimates may be somewhat overestimated. Brick kilns likely become more efficient over time, though the effect would be partially offset by the fact that later brickmaking made use of steam engines for mechanical work. Per capita brick production also rises slightly during the 40 years of reported data shown here, though data are noisy. (The median is 87 bricks/person/year but 1890 is an excursion to over 125.)

Table S9. Fuels in brick and tile production, 1800–1910. Bolded values are given directly in primary sources; unbolded values are derived by proxy. Primary sources are the Census Reports on Manufactures, 1880–1910 (1). Note that the 1880 Census provides the wood use of the industry, but no other fuels; we have allocated the remaining energy to coal. Fuel shares are estimated as described in text. For pre-1910 years, we assume a fixed energy intensity of a 0.58 Watts per brick per year, i.e. $\sim$18 MJ/brick, based on 1910 values. Where the number of bricks is not recorded, we assume constant per capita of 72.5 bricks/person/year, based on 1870 values. Coal and metal quantities are given in thousands of tons. The heat content for a cord of wood and a ton of coal are roughly comparable: we assume 24 and 25M BTU/ton for bituminous and anthracite, respectively, and 21M BTU/cord for wood.

year	bricks (bil.)	wood share	anth. share	bit. share	coke share	coal share (total)	wood	anth.	bit.	coke
1800	0.39	1.00	-	-	-	-	278	-	-	-
1810	0.53	1.00	-	-	-	-	380	-	-	-
1820	0.70	1.00	-	-	-	-	505	-	-	-
1830	0.93	1.00	-	-	-	-	674	-	-	-
1840	1.24	1.00	-	-	-	-	895	-	-	-
1850	1.68	1.00	-	-	-	-	1216	-	-	-
1860	2.28	0.80	0.20	0.00	0.00	0.20	1319	288	0	-
1870	**2.80**	0.50	0.40	0.10	0.00	0.50	1011	707	202	-
1880	**3.82**	0.42	0.35	0.23	0.00	0.58	**1158**	845	634	-
1890	**8.05**	0.15	0.55	0.30	0.00	0.85	872	2797	1738	5
1900	**7.49**	0.15	0.08	0.77	0.01	0.85	811	355	4164	23
1910	**9.92**	**0.15**	**0.04**	**0.81**	**0.01**	0.85	**1070**	**236**	**5773**	**41**

7.2.3. Glass. Glassmaking is an energy intensive process, and U.S. glassworks tended to cluster geographicaly around energy sources. Pennsylvania (and Pittsburgh in particular) became the center of U.S. glassmaking in the mid-19th century because of its low-cost coal, and coal use in glasssmaking came earlier than in the other industries we track (95). Early coal in glassmaking was predominantly anthracite, both for its cheapness and abundance in Pennsylvania (95), and more generally because it was valued for its low impurities (90). Glassmaking also differs from the other industries we track in being an early adopter of natural gas, beginning already in the 1880s. Given the limited pipeline network of the time, glass factories migrated instead to their energy sources, and sites with natural gas reserves came to be glassmaking centers, including the "gas belt" of Ohio and Indiana (at least until local supply was exhausted, at which point the glass industry would decamp again). Some glassworks even operated their own gas wells (95).

Unfortunately no firm statistics exist on fuel uses in early glassmaking, or even on the quantity of glass produced. Glass is recorded in the Census Report on Manufactures at all only from 1910, when the Census increased the detail of its industrial reporting in general. We therefore estimate glass energy use using indirect proxies: the number of glassworkers, an employment category recorded in the Census from 1850 on, and for earlier years by the number of operational glassworks, using numbers collected in a 1997 NBER paper (95). We derive a scaling factor of 27.6 tons coal equivalent/year per employed worker from the 1910 Report on Manufactures, and 3500 tons coal equivalent/year per operational glassworks, derived from our estimate of 1850 energy use for 94 glassworks. This scaling may produce an overestimate of early glass production, since glass factories were growing larger during the period in which we have data, rising from an average of about 60 employees per glassworks in 1850 to nearly 200 in 1910.

Fuel shares in glassmaking are even more difficult to assign. We assume that early coal use was small until the 1840s, and assign a 1% share based on the share of the national urban population living in Western Pennsylvania in the early 1800s (1). Coal use rose quickly, presumably aided by the growing railroads. Anthracite is known to be the primary fuel in glassmaking already in the 1850s (90), but is completely extirpated from the industry when detailed records begin in 1910. Similarly, natural gas use rose quickly after its introduction in the 1880s, and made up over half of glassmaking fuel use in the 1910 Census. We construct a timeline of fuel shares that matches these rapid transitions. Results are shown in Table S10.

Table S10. Fuels in glass production, 1800–1910. Bolded values are given directly in primary sources or well documented secondary reports, and unbolded values are estimated by proxy. Sources are the Census Reports on Manufactures, 1850–1910 (1); and an NBER report for glassworks numbers (95). For 1850–1900 we use a scaling factor of 27.6 tons coal equivalent/year per employed worker, derived from the 1910 Report on Manufactures, and for 1800–1840 3500 tons coal equivalent/year per operational glassworks, derived from our estimate of 1850 energy use for 94 glassworks. Glassmaking differs from other index industries in its early use of anthracite coal (90) and its shift to natural gas towards the end of the century (95); note that the remaining 3% of energy in 1910 not shown here was derived from petroleum. We construct an estimated timeseries of fuel shares based on anecdotal reports of usage. Coal and metal quantities are given in thousands of tons, and wood values in thousands of cords. The heat content for a cord of wood and a ton of coal are roughly comparable: we assume 24 and 25M BTU/ton for bituminous and anthracite, respectively, 24.8M BTU/ton for coke, and 21M BTU/cord for wood.

year	wood share	anth. share	bit. share	coal share (total)	nat. gas share	glassworks	workers (1000)	wood	anth.	bit.	coke
1800	0.99	0.01	0.00	0.01		**10**	-	38	0	-	-
1810	0.99	0.01	0.00	0.01		**20**	-	77	1	-	-
1820	0.99	0.01	0.00	0.01		**40**	-	154	136	-	-
1830	0.99	0.01	0.00	0.01		58	-	223	1971	-	-
1840	0.80	0.20	0.00	0.20		76	-	236091	51645	-	-
1850	0.50	0.40	0.10	0.50		**94**	**6**	182505	127753	36501	-
1860	0.17	0.50	0.33	0.83		**112**	**9**	93077	239538	180680	-
1870	0.17	0.50	0.33	0.83		**154**	**15**	155129	399229	301133	-
1880	0.13	0.45	0.42	0.87	0.00	**169**	**24**	189805	574890	613216	-
1890	0.05	0.17	0.53	0.70	0.25	**294**	**45**	139000	403338	1454457	-
1900	0.03	0.08	0.40	0.48	0.50	**355**	**53**	80606	211592	1289701	-
1910	**0.00**	**0.00**	**0.44**	**0.45**	**0.51**	**363**	**69**	**12488**	**17906**	**1859001**	**17393**

7.2.4. Cement. Cement, the binding agent in concrete, is a critical construction material. The first cement plants in the U.S. were built in the late 1810s for producing waterproof mortars for the lining and lockworks for the Erie Canal (96), but the bulk of the industry's growth came after 1880. Two developments drove that growth: Portland cement that could be made from more common materials, and reinforced concrete that that allowed its wider use as a building material.

Records of kiln fuel in U.S. cement plants are scarce. Cement production requires substantial heat, and price is a critical factor in fuel choice. While the first rotary kilns of the 1890s were oil-fired, cheaper coal was rapidly substituted. It is generally accepted that Portland cement both drove the industry's expansion in the 1890s and 1900s and was overwhelmingly produced using coal kilns (96). A 1911 report by the U.S. Geological Survey lists 87 out of 115 cement plants as powered by bituminous coal, using 200–300 pounds of coal to produce 380 pounds of cement, a scaling factor of ~ 0.65 (96). The remaining plants in 1911 are largely petroleum (19), plus 9 powered by natural gas, with the diversity likely due to the difficulty of shipping cement, which meant that plants were dispersed and used whatever fuel was locally available. All the cement plants in California in 1911, for example, used petroleum from the local oil industry.

For lack of detailed data, we estimate energy usage in the early cement industry based on 1910 reported values (1), scaling it to total cement tonnage produced and shipped (6) (Table S11). The resulting scaling factor is only 0.47 tons coal per total tons cement. We assign the same fuel proportions to cement that we do to iron/steel, with the assumption that the 18% of cement fuel in 1910 from natural gas and petroleum scaled up linearly from zero in 1890 to 18% in 1910. The assumed proportions of anthracite to bituminous are highly uncertain, but the overall transition from wood to coal in the cement industry should be reasonably robust.

Table S11. Fuels used in cement production, 1800-1910. Bolded values are given directly in primary sources (Census Reports on Manufactures, 1870–1910 (1)), and unbolded values are estimated by proxy, using a conservative scaling of 0.47 tons coal equivalent per total tons cement, derived from 1910 values. In the absence of concrete data on fuels used in the nineteenth century for cement aside from the rapid expansion fueled by coal, we assign cement production the same fuel shares as iron/steel production. Coal and cement quantities are given in thousands of tons, and wood values in thousands of cords. The heat content for a cord of wood and a ton of coal are roughly comparable: we assume 24 and 25M BTU/ton for bituminous and anthracite, respectively, and 21M BTU/cord for wood.

year	wood share	anth. share	bit. share	coal share (total)	cement shipments	wood	anth.	bit.	coke
1800	1	0	0	0	**0**	-	-	-	-
1810	1	0	0	0	**0**	-	-	-	-
1820	1	0	0	0	**5**	2	-	-	-
1830	1	0	0	0	**17**	7	-	-	-
1840	0.8	0.2	0	0.2	**73**	23	5	-	-
1850	0.5	0.4	0.1	0.5	**188**	36	25	7	-
1860	0.17	0.5	0.33	0.83	**280**	18	47	36	-
1870	0.17	0.5	0.33	0.83	**377**	25	64	48	-
1880	0.13	0.45	0.42	0.87	**354**	18	54	57	-
1890	0.065	0.225	0.71	0.94	**1326**	33	101	364	-
1900	0.025	0.075	0.90	0.98	**2939**	28	74	1021	-
1910	**0.001**	**0.06**	**0.94**	**1.00**	**13266**	6	259	4816	4

7.3. Railroads.

The first decades in the 19th century saw the introduction in the U.S. of the first forms of motorized transport, steamboats and locomotives. Engine-powered steam locomotives were first operated in the U.S. in the early 1830s, serving passenger markets with coal-burners imported from Britain. The U.S. industry quickly turned to wood, however, which was cheap and widely available (convenient for frequent refueling), and in 1840 U.S. railroads were essentially 100% fueled by wood (5, 97).[10] Wood use at the time was not tracked in government reports, but railroads have been the subject of extensive historical study and their transition from wood to coal is reasonably well documented. Although some experimentation with coal happened in the 1850s, and railroads that served the anthracite fields often used the fuel they were hauling (99), a widespread transition to coal is widely acknowledged to occur only in the 1870s (e.g. (97)). The transition was nearly complete by 1880, when multiple government documents report ∼90% use of coal, including the 1880 Census *Report on Manufactures* (1) and the U.S.G.S.-issued *Mineral Resources of the United States* series, which reports railroad coal use from 1880 (83, 84). Railroad fuel is well-recorded by the time locomotives switched to diesel-powered engines in the 1940s (55).

To estimate absolute usage by railroads we make separate estimates of railroad fuel consumption and of the share of different fuels. Where data is unavailable we scale to proxies. Results are shown in Tables S12

Railroad reported total fuel: The earliest government estimates of coal and wood use in railroads are for the year 1880, appearing in the U.S.G.S. *Report on Mineral Resources* (83) and the 1880 "Forest Census" (1). Fuel amounts are reported regularly after 1900 for bituminous coal and fuel oil by the 1931 Mineral Resources report and in Schurr and Netschert. We estimate energy use in prior years by scaling to proxies.

Railroad proxies: For years with no recorded fuel data, we estimate total railroad energy use in two ways. Before 1852, we index railroad energy use to the only available statistic: track mileage, from HSUS. From 1852 onwards, we can use railroad ton-miles (tons of freight carried × miles traveled), also from HSUS (6). We index to the first records of total fuel burnt, the 1880 values from unpublished estimates compiled in the 1931 Report on Mineral Resources (84), which produce a scaling factor of 4.95 tons coal per 10,000 ton-miles traveled. Note that benchmarking to 1880 data means implicitly assumes a constant efficiency of railroad engines, and likely underestimates early fuel usage. Applying that factor in turn to track in 1850 gives us a secondary scaling of 42 tons coal per year per mile of track. We use the earliest possible date for this scaling to account for changes in railroad practices.

While some historians advocate scaling to track-miles throughout (97), the two methods would give very different results, since the freight carried per mile of track rose strongly over time. In 1850, the railroad system carried less then 100,000 ton-miles of freight per year per mile of installed track; in 1870 the number is over 250,000 and in 1900 over 700,000. (By 1945, the value is over 3 million, since freight transport continued to increase even while track mileage decreased.) We scale by ton-miles wherever possible since the measure is directly related to the work done by a railroad engine.

Railroad fuel shares: Shares of wood, anthracite, bituminous, and fuel oil for each year in Table S12 are either calculated from primary sources or taken from secondary sources (5, 97, 99, 100). When the split between bituminous and anthracite coal is not reported, we assume for convenience that the proportions are constant at their last reported value. Anthracite coal use is tracked inconsistently and much less precisely in government statistics than is bituminous[11]

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[10] Exceptions include the Baltimore and Ohio lines, which burnt at least some anthracite from their inception in the 1830s (97).

[11] In the *Annual Report on the Statistics of Railways in the United States*, issued regularly by the Commissioner of Railroads, anthracite usage is reported only from 1920–1930 even though early railroads burned at least some anthracite (99).

Table S12. Fuels in railroads, 1830–1945. Railroad mileage and ton-miles from Historical Statistics of the United States (6). Bolded values are given directly in primary sources: reports on the *Mineral Resources of the United States* 1893 and 1931 (83, 84), the latter with extensive data back to 1880, and Schurr and Netschert (for fuel oil and diesel) (5), the 1925 Report of the Commissioner of Railroads (98) for a brief span in the 1920s, and the *Report on Forests of North America* from the 1880 Census (1). Unbolded values are taken from secondary sources or estimated by proxy, using 0.01 tons coal equivalent per ton-mile traveled from 1850–1880, and 880 tons coal/year per mile of track from 1830–1840. Coal quantities are given in thousands of tons, wood in thousands of cords, and fuel oil and diesel in millions of gallons. Energy densities are 24 and 25M BTU/ton for bituminous and anthracite, 21M BTU/cord for wood, and 129.5 and 135 BTU/gal for fuel oil and diesel.

year	bit. Share	anth. Share	wood share	fuel oil share	diesel share	mileage	ton-miles (bil.)	bit.	anth.	wood	fuel oil	diesel
1830	-	-	1	0	-	**23**	-	-	-	1	-	-
1840	-	-	1	0	-	**2818**	-	-	-	119	-	-
1850	0.04	0.01	0.95	0	-	**12908**	**1**	15	3	518	-	-
1860	0.09	0.01	0.9	0	-	**30626**	**3**	104	10	1463	-	-
1870	0.49	0.01	0.5	0	-	**52922**	**14**	3283	59	3350	-	-
1880	0.88	0.02	0.1	0	-	**98262**	**40**	17354	345	**1972**	-	-
1885	0.94	0.02	0.04	0	-	**128320**	**49**	21927	280	640	-	-
1890	0.97	0.025	0.005	0	-	**166703**	**78**	**26500**	598	137	-	-
1900	0.97	0.025	0.005	0	-	**197237**	**142**	**53400**	1204	275	-	-
1905	0.97	0.025	0.001	0.00	-	**224363**	**186**	**81000**	1827	84	**15**	-
1910	0.97	0.025	0.001	0.00	-	**243979**	**255**	**106000**	2390	109	**20**	-
1915	0.97	0.025	0.001	0.05	-	**254251**	**277**	**117000**	2639	121	924	-
1920	**0.90**	**0.02**	**0.00**	**0.08**	-	**252845**	**414**	**124700**	**2473**	160	**1828**	-
1923	**0.87**	**0.02**	**0.00**	**0.11**	-	**250222**	**416**	**117247**	**2679**	128	**2334**	-
1925	**0.85**	**0.02**		**0.13**	-	**249398**	**417**	**117714**	2427		**3033**	-
1930	**0.83**	**0.02**		**0.15**	-	**249052**	**386**	**98400**	2212		**2852**	-
1935	**0.82**	**0.02**		**0.15**	-	**241822**	**284**	**77109**	1733		**2337**	-
1940	**0.82**	**0.01**		**0.17**	**0.00**	**233670**	**375**	**85130**	1003		**2783**	**66**
1945	**0.78**	**0.02**		**0.19**	**0.02**	**226696**	**684**	**125120**	2551		**4818**	**433**

7.4. Steamboats and ocean-going steamships. River and lake steamboats and ocean-going steamships have very different energy histories, but must be treated together here because they are combined in the only early government records of U.S. shipping. We consider here only vessels using external-combustion steam engines. By the time internal combustion engines came into use, their fuel use was separately tracked in government statistics.

The American steamboat is the earliest use of a steam engine for transportation, preceding the British locomotive. Steamboats replaced the human-powered keelboat on the Mississippi and other western rivers, allowing easy upstream transport of passengers and goods (49, 106). (Note that our inventory would not include human labor to pole a keelboat.) From the 1820s until the Civil War, steamboats were the dominant form of commercial transport for the interior U.S. (106). The earliest steamboats were entirely wood-powered: steamboats rarely carried more than a day's fuel, and either cut wood from the riverbanks or bought new supplies each day (48). At least some coal was used in 1830 (49), and coal usage became more common in the 1840s and 50s, but most steamboats used fireboxes capable of burning either fuel and often combined both (48, 49). In the 1860s, coal mines in Illinois and Missouri allowed wider use of coal, but steamboats continued to burn substantial wood til the 1890s.

Ocean-going ships never used wood. These ships cannot refuel en route and must carry their energy source, limiting them to only energy-dense fuels. Their transition to steam power also came later, when engines had become efficient enough to manage an Atlantic crossing, and later still for Americans than for the British: sail-powered clipper ships dominated U.S. international transport til after the Civil War (48). The coal era for U.S. shipping was therefore fairly short, since the pressure for energy-dense fuels led ocean-going ships to convert to fuel oil when it became available in the 1910s (101).

Historical statistics for ships and boats are complicated, because they were aggregated in HSUS statistics until 1920. HSUS tabulated only combined motorized ship gross tonnage (GT, a measure of ship volume as the mass of water displaced), and did not track fuel usage at all (6). Fuel records become comprehensive only from 1920 onward. At that point HSUS also began separating maritime and river boats, as well as coal- and oil-burning vessels, and tracked both coal and oil usage (6). We have a few prior primary-source estimates but largely estimate fuel use by proxy using tonnages; We disaggregate riverboats and ocean steamships using HSUS records of the location of construction of new ships. This division places roughly half of all steam-powered tonnage on "western rivers" in the 1830s, falling to 20% by 1900 (6).

For *steamboats*, we take shares of wood and coal from the historical study of Hunter and Hunter (49) and otherwise interpolate. We estimate total energy use using our only primary datapoint, the 1880 Census *Report on Forests of North America* (1) which reported cords of wood used in steamboats; wood and coal shares at the time were roughly equal. The resulting conversion is $\sim$6 tons coal equivalent per year per GT. This value is broadly consistent with contemporary anecdotal evidence. In 1848, for example, the Lake Michigan sidewheel steamer *Empire* at 1140 GT was said to have burned 9100 cords/year or 7 tons coal equivalent/year/GT (48). Note that we implicitly assume that all pre-1880 steamboat engines had 1880 efficiencies, likely underestimating early fuel use. We also assume that coal and wood can be scaled by their energy content, but contemporary records suggest that wood-burning steamboats may have required additional fuel use: anectoally, they equate a cord of wood to 3–4 tons of coal (49, 102).

For *steamships*, we have records of coal from 1890 in the U.S.G.S. *Mineral Resources* reports (83, 84), and all fuels from 1920 via (5). The only fuel share that needs to be estimated is the earliest fuel oil used. We assume that oil usage begins in 1905 (101, 103) and that its share increases linearly to its 1920 value. For pre-1890 fuel use, we benchmark to tonnage using 1890 values. Results are shown in Table S13. The derived conversion factor is 1.7 tons coal equivalent per year per GT, roughly consistent with the global estimates of Endresen et al. (105) for 1925, who derive a ratio of around 1.4 tc/year/GT (of which a quarter of the tons equivalent was actually oil; note that oil-fired boilers were more efficient). The scaling appears low relative to reported performance of 19th- and early 20th-century ships while steaming of between .02-.04 tc/day/GT (Table S14, from (104)); at these rates an overall usage of 1.7 tc/year/GT would imply only 40-85 days/year under steam. The discrepancy may be related to purchase of coal abroad that was not recorded by HSUS, though on the other hand HSUS coal totals may include foreign-flagged ships docking at U.S. ports. (In general, disentangling U.S. shipping from the global energy supply chain is not simple.) Note that coal-powered steamships experienced relatively small efficiency gains over time, as the benefits of improved engines largely went to increasing engine power and ship speed rather than to reducing fuel consumption (Table S14).

Table S13. Fuels in shipping, 1810–1945. Bolded values are given directly in primary sources, with tonnage from HSUS (6) and fuel figures from *Mineral Resources of the United States* reports(83, 84) and from the Census via (5). Tonnages before 1920 are allocated to oceangoing steamships or river/lake steamboats as described in text. Unbolded figures are estimated by proxy, using 1.7 tons coal equivalent/year per GT for steamships and 6 tc/year/GT for steamboats. Fuel shares are determined as described in text. Shipping tonnage is given in thousands of gross tons, coal in thousands of tons bituminous, wood values in cords, and petroleum products in millions of gallons.

	ocean-going vessels										vessels on “western rivers” and lakes				
year	coal share	fuel oil share	diesel share	tonn. steam	tonn. coal	tonn. oil	tonn. diesel	coal marine	fuel oil marine	diesel marine	wood share	coal share	tonn. boats	wood boats	coal boats
1810	1.00	0.00	0.00	**1**	-	-	-	1		-	**1.00**	**0.00**	**1**	3246	0
1820	1.00	0.00	0.00	**11**	-	-	-	19		-	0.95	0.05	**11**	69179	3
1830	1.00	0.00	0.00	**34**	-	-	-	59		-	0.92	0.08	**30**	185206	14
1840	1.00	0.00	0.00	**130**	-	-	-	226		-	0.89	0.11	**71**	417257	46
1850	1.00	0.00	0.00	**395**	-	-	-	686		-	0.78	0.22	**131**	689854	172
1860	1.00	0.00	0.00	**694**	-	-	-	1205		-	**0.65**	**0.35**	**174**	778648	360
1870	1.00	0.00	0.00	**860**	-	-	-	1493		-	**0.55**	**0.45**	**215**	824499	585
1880	1.00	0.00	0.00	**970**	-	-	-	1684		-	**0.50**	**0.50**	**242**	**794775**	795
1885	1.00	0.00	0.00	**1196**	-	-	-	2076		-	0.31	0.69	**299**	794775	1538
1890	1.00	0.00	0.00	**1487**	-	-	-	**2581**		-	0.06	0.94	**372**	157108	2281
1900	1.00	0.00	0.00	**2126**	-	-	-	**3690**		-	0.01	0.99	**532**	32473	3215
1905	1.00	0.00	0.00	**2993**	-	-	-	**5195**		-	**0.00**	**1.00**	**748**		4521
1910	0.91	0.09	0.00	**3920**	3254	666	-	**6804**	126	-			**980**		5922
1915	0.80	0.20	0.00	**5944**	3982	1962	-	**8200**	370	-					
1920	**0.63**	**0.36**	**0.00**	**13466**	**7551**	**5915**	**24**	**10486**	**1114**	12			**1510**		9126
1923								**5000**							
1925	**0.21**	**0.76**	**0.03**	**14495**	**5512**	**8931**	**254**	**4866**	**3330**	127			1102		6662
1930	**0.13**	**0.79**	**0.07**	**12775**	**4209**	**8429**	**715**	**3497**	**3954**	358			**842**		5087
1935	**0.08**	**0.81**	**0.11**	**11433**	**3496**	**7748**	**841**	**1576**	**3132**	421			**699**		4225
1940	**0.08**	**0.76**	**0.17**	**10102**	**3159**	**6943**	**1090**	**1426**	**2597**	**545**			**632**		3818
1945	**0.06**	**0.82**	**0.11**	**28669**	**2931**	**25737**	**1433**	**1785**	**4247**	**562**			**586**		3542

Table S14. Coal usage of selected steamships, 1819–1892, from Maginnis, *The Atlantic Ferry*, 1892 (104). Fuel usage is given in tons coal / day while steaming. Early paddlewheel steamships (“PS”) were replaced by more efficient screw propeller steamships (“SS”), with either compound or triple-expansion engines from the 1870s. Engine improvements appear to be used for speed rather rather fuel efficiency.

Date	tc/day/GT	Name	tc/day	GT	Type
1819	.041	*Savannah*	13	219	PS
1838	.034	*Sirius*	24	703	PS
1837	.025	*Great Western*	33	1340	PS
1843	.020	*Great Britain*	65	3270	SS
1856	.045	*Persia*	150	3300	PS
1862	.043	*Scotia*	165	3871	PS
1866	.023	*Manhattan*	65	2869	SS
1866	.040	*City of Paris*	105	2651	SS
1869	.036	*City of Brussels*	110	3081	SS
1869	.041	*America*	185	4454	SS
1874	.022	*Britannic*	110	5004	SS-compound
1879	.024	*Arizona*	125	5147	SS-compound
1883	.036	*Oregon*	265	7375	SS-compound
1883	.011	*British King/British Queen*	38	3412	SS-compound
1892	.030	*Campania/Lucania*	400	12,950	SS-triple

7.5. Fuel wood. Timber was exceptionally abundant in depopulated North America relative to European regions (63, 64), and Americans were known for their profligate wood use (5).

Residential consumption is widely acknowledged to dominate early U.S. energy use. Contemporary letters describe frigid houses in winter, with enormous quantities of wood burning in inefficient open hearths (5, 12, 13). According to Schurr and Netschert (5), "More than nine-tenths of [wood use] was used in households, including... drying of tobacco and the smoking of meat. About three-quarters of the total was burned in open fireplaces." The practice of heating with fireplaces persisted through much of the 19th century. Adoption of more efficient stoves occurred only slowly, likely driven by multiple factors, including the depletion of the forests and the end of the era of land-clearing, the rise of American manufacturing that lowered the cost of factory-made stoves, and the spread of railroads that allowed carrying heavy goods to rural locations (5, 13).

The first comprehensive estimate of national fuel wood use came only in 1880, when the census *Report on Forests of North America* (1) surveyed wood consumption across sectors, but wood use has been extensively studied by historians. We base our estimate on the timeseries by Schurr and Netschert (5), who estimate residential use from 1850 onwards, starting at an annual use of 4.4 cords of fuel wood per person (along with the equivalent in coal of less than 1/2 cord of wood), and gradually falling to intersect the reported 1880 value of 2.7 cords per person (plus coal equivalent to 1.8 cords; i.e. the decline in residential wood use over this period was driven primarily by substitution of coal). Household wood usage continued to fall in both per capita and absolute terms for the rest of the 19th century, and was occasionally but inconsistently estimated by government statisticians in the 20th century.

For years before 1850, we use a scaling of 4.5 cords/person/year, slightly above Schurr and Netschert's 1840 value. This scaling is consistent with estimates from other historians. Williams (*Americans and Their Forests: a Historical Geography*, 1989 (125)) estimates decadal wood use for U.S. household heating from 1700 to 1769, with about 5.4 cords/person/year in the 1760s and 6.4 in the 1700s. Reynolds and Pierson (124) estimate household wood use from the 17th through early 20th centuries in different geographic regions, with estimates ranging from 3.25 cords/person/year in the South Atlantic states to nearly 5 cords/person/year in New England. These values exceeded *total* energy consumption across all sectors in European contemporaries, even in cold countries (See (9) and its Appendix 4).

Transportation wood use in railroads and steamboats represents only a small fraction of total U.S. wood use. In the 1880 *Report on Forests of North America*, railroads consumed under 2 million total cords or 0.04 cords/person/year, ∼1.4% of total U.S. wood use. Our estimation process is described in detail in Sections 7.3 and 7.4 above. The resulting estimates for total fuel wood consumption in transportation are broadly similar to those by other historians, but fairly conservative. For example, Schurr and Netschert cite some contemporary estimates of as much as 6 million cords of wood used by railroads in the 1860s, and White (*A History of the American Locomotive*, (97)) estimates 6 million cords in 1870; we estimate 1.5 and 3.4 million cords in 1860 and 1870, respectively.

Industrial fuel wood use in the 19th century was also small relative to residential consumption (124). Even in the mid-nineteenth century, with the growth of manufacturing, less than 10% of U.S. fuel wood went to industry. Early industrial wood use was dominated by iron and steel production, since charcoal was the primary energy source for smelting and metalwork until mid-century (see Table S8). In the 1880 census report, ironmaking consumed a similar amounts of wood as railroads, ∼1.2% of total wood use and nearly half our estimated total industrial wood use. Our estimation of wood use in ironmaking and in industry in general is described in detail in Section 7.2 above. Resulting values are broadly consistent with those of other historians. Schurr and Netschert construct an industrial fuelwood estimate for 1879 that is only 60% of our value (2.5 as opposed to 4.2 million cords), but it is likely based on a more limited survey of manufactures and mining. (The 1880 *Report on Forests of North America* surveyed only brick and tile, salt, and iron and steel production.)

From 1920 to 1949, sectoral usage of wood is not directly reported in government statistics. We estimate industrial fuel wood consumption in this period based on total fuel wood consumption from Schurr and Netschert (5) and an assumed industrial share based on 1910 data. (In the Census *Report on Manufacturers* (1), industry used ∼6% of total U.S. fuel wood.) We scale that proportion linearly to 10% in 1935, when the Great Depression appears to have increased reliance on fuel wood. The next available data, from the EIA in 1949, suggest that industrial use held steady at around 10% of total fuel wood consumption (2, 5). This use is largely by manufacturers of paper and wood products, who burn their scrap and waste wood for heat and on-site electricity generation.

7.6. Animal feed.

Draft animal consumption of biomass makes up the second most important category of early U.S. energy use, after residential heating with fuelwood. We estimate this energy contribution based on the number of draft animals and assumptions of the feed input per animal. Table S15 shows draft animal numbers and Tables S16-S17 show estimates of feed inputs.

Draft animal numbers. Detailed statistics on draft animals in the U.S. are available from the 1850 Agricultural Census onwards (3), which counts horses used for transportation separately from animals used for farm work. In 1850, the U.S. had 1 agricultural draft animal for every 3.5 people, and 1 transportation horse for every 4.3 urban residents. (Comparison to the urban population is the most relevant; urban residents are taken from the Census and make up less than 15% of total U.S. population in 1850.) Post-1850 numbers are relatively constant, e.g. the proportion of farm work animals remains 1 per 3.4 people in 1900. In earlier years, historians assume slightly larger numbers. For the years 1800–1840, we assume fixed proportions of of 3 people to each agricultural draft animal, and 3 urban people for each transportation horse, using estimates derived by Greene (2008), *Horses at Work* (107). Horses on farms are tracked until quite late in the Agricultural Census, only disappearing in 1954 after they become a negligible input into agriculture (3), but horses in transportation are tracked only to 1900. We estimate their post-1900 decline from the decline in selected cities given in McShane and Tarr, *The Horse in the City*

(18): namely, that the number of horses in urban transportation halved from 1900 to 1910, declined by another third from 1910 to 1920, and then declined to essentially zero by 1930.

To allow treating feed inputs differently for horses, mules and oxen, we also estimate their proportions in agriculture. (However, this differentiation by species only matters after 1850, when Census also counts draft animal species individually.) Oxen provided the bulk of farm work in Colonial America, but their importance declined over time as U.S. farmers turned to horses instead (107), and oxen nearly disappeared in the U.S. as a working animal by the end of the 19th century. In 1850, the Census counted over 5 million horses (of which 4.3 million worked on farms), 1.7 million oxen, and half a million mules (1), i.e. agricultural draft animals had proportions of 70% horses, 23% oxen, and 7% mules. By 1900, the reported proportions were 83% horses, only 3% oxen, and 14% mules. For the periods before Census data exist, we assume oxen represented 2/3 of all draft animals in 1790, with proportion declining linearly to that reported in 1850 (3).

Table S15. Draft animals used in agriculture and transport, 1800–1850. Bolded values are reported directly in sources (3), and unbolded are estimated by proxy. For pre-1850 years, we assume a ratio of 1 agricultural draft animal for every 3 people and 1 transportation horse for every 3 urban residents (107); see text for proportions. This scaling means the numbers of animals in transportation rises faster than those on farms, since U.S. urban residents grew from 6.1% of the population in 1800 to 15.4% in 1850 (1).

		Agriculture		Transportation
Year	Horses	Mules	Oxen	Horses
1800	619500		1150500	117527
1810	965333		1448000	183136
1820	1606667		1606667	304805
1830	2572000		1714667	487941
1840	**4335069**		1700000	822417
1850	**4337000**	**559000**	**1700711**	**822784**

Table S16. Reported feed inputs for working horses, 1810–1922. A "low estimate" is given for horses which are explicitly described in the primary source to be not of peak condition or not working particularly hard; a "high estimate" is for those explicitly described as hard working or in peak condition. Where both are provided, they represent a range given by the primary source. Estimates demonstrate a clear upward trend in feed requirements, related to breeding of more powerful draft horses. Note that even the lowest value of ∼1200 Watts exceeds the estimate of (70), who assume a fixed value equivalent to 915 Watts. **This document describes feed requirements for recovering draft horses used in the Civil War, so we call it a "high" estimate even though the title describes "disabled horses".*

Citation	Year	Low Estimate (W)	High Estimate (W)
Knowlson, *The Complete farrier, or, Gentleman's travelling companion.*(109)	1810	1355.7	1694.7
Stewart, *Stable economy.*(110)	1838	1202.9	1225.0
Rarey, *Taming or breaking the horse.*(111)	1858		1152.2
Holt, *Feeding disabled horses.**(112)	1861		1554.5
Jennings, *The horse and other live stock.*(113)	1866	1830.9	1938.6
Sanborn, *Feeding hay and grain.*(114)	1892	1550.3	
Gleason, *Gleason's horse book and veterinary adviser.*(115)	1892	1737.4	2041.4
Mills, *Relative value of corn and oats for horses.*(116)	1894	1252.8	1338.7
Nourse, *Silage for Horses.*(117)	1897	1570.6	
Merrill, *Horse Feeding.*(118)	1902		2116.0
Langworthy, *Principles of Horse Feeding.*(119)	1903	1198.3	
Obrecht, *Feeding Farm Work Horses.*(120)	1911		1853.8
Woodruff, *The Economics of Feeding Horses.*(121)	1912		1779.4
Carroll, *Feeding Work Horses.*(122)	1920	1327.1	1724.7
Edmonds, *Feeding farm work horses and mules.*(123)	1922	1739.8	2096.0

Table S17. Final values used for converting number of horses to Watts of energy input. we use the estimates provided in Table S16 to generate a rolling average of horse feed inputs. Values increase by 35% over a half-century, broadly consistent with commonly reported increases of ∼50% in the power per horse across the late nineteenth century (McShane and Tarr, 2011 (18)).

Year	Watts per horse per day
to 1860	1300
1870	1400
1880	1500
1890	1600
1900	1700
1910	1750

Animal feed inputs: Animal feed input cannot be derived with a constant scaling, since targeted breeding in this time period changed the horse body considerably. The average draft horse became roughly 50% larger, stronger, and therefore more energy-demanding over the course of the 19th century (18). Before the 19th century, livestock varied widely across time and space but breeds were largely specific to areas. Afterwards, the transportation revolution allowed farmers in the U.S. and Europe more ability to select the best-suited animals, and several optimized breeds spread throughout the world (108).

We determine how the average feed intake of draft horses changed during this period by using a set of primary sources that tracked horses on experimental or recommended diets. To convert quantities of feed into Watts, we use physical assumptions for corn, hay, and silage summarized in Section 6.3. Table S16 lists all sources consulted here, their years of publication, and the suggested range of feed intakes. Sources generally show an overall upward trend, but individual estimates differ. We weigh most heavily those sources that specifically considered working animals (rather than, for example, recreational breeding guides), and construct the timeseries of Table S17 for the evolution of draft horse energy intake over time. Feed intake values increase by 35% over a half-century, broadly consistent with the reported $\sim$50% gain in power per horse (18).

Data on feed for oxen and mules is less available than that for horses. Since all were said to be roughly equivalent in work output in the nineteenth century (37), for convenience we assume that all draft animals have the same energy inputs prior to 1860, and that afterwards oxen and mules remain at these values while horses evolve.

The increased power and appetite of the horse meant that even though per capita numbers of agricultural draft animals remained relatively constant during the 19th century, their energy inputs became a larger part of the U.S. energy economy, rising from <400 W/cap. in 1850 to 500 W/cap. in 1900. The increase likely reflects the fact that draft animals pulled increasingly large and complex farm equipment, including combine harvesters.

Per capita agricultural energy use fell substantially in the 20th century with the adoption of the tractor. While an equine “bio-engine” and an internal combustion engine have similar efficiencies at converting input fuel to mechanical work, animals also have basal metabolisms, and must be fed regardless of whether or not they are working.

7.7. Biological Oils. Biological oils, generally used for indoor lighting, represent a very small part of total U.S. energy use, but a disproportionately valuable one. Liquid lamp fuels such as whale oil or turpentine-based camphine comprise less than 1 Watt/capita of usage, <0.03% of total energy use in any given year, but were many times more expensive than other energy sources. The total market value of biological oils in 1860 ($20 million) was over half that of all coal and coal products ($38.8 million) (70), despite contributing less than 1% as much energy.

In this work we take estimates for 1840–1860 for each of the biological oils from the inventory of O’Connor and Cleveland (2014) (70). That inventory derived the amount of whale oil harvested by American whalers from various primary sources, and combined this estimate with Census statistics about the production of other biological oils. Because there are no published estimates of all biological oil use after 1860, we estimate post-1860 values by assuming that per-capita use halves each decade after 1860, from 2.8 W/capita to 0 W/capita in 1920, a decline based on known periods of growth and decline for each industry (see Zallen, *American Lucifers* (28)).

7.8. Water Power, Mechanical. Textile mills of the early 1800s are known to be water-powered (20), though no aggregate data on their energy use exist. Water power was directly reported in the Census *Report on Manufacturers* only in later years: 1904, 1909, 1914, 1917, and 1919 (1). We therefore estimate hydropower in the 19th century using the total pounds of finished cotton goods produced as a proxy, scaling this timeseries by the relationship between all industrial hydropower and cotton goods manufacture at the earliest known point, 1870. This approach implicitly assumes that the proportion of textile production to all water-powered manufacturing remained the same from 1800–1870. Water power between 1890 and 1920 is reported in the 1920 Census Report on Manufactures (1). For the post-1850 period, however, we are working entirely with published estimates (5) rather than by proxy value. Commodity statistics and inferred waterpower up to 1890 are shown in Table S18.

Table S18. Industrial water power, 1800–1890. Estimates of hydropower from 1870 are taken from Schurr and Netschert (5). For earlier years, we index water power to the domestic consumption of cotton in textile manufacturing from HSUS (6). Cotton mills generally employed water power in the early industrial period, and were one of its largest consumers, especially in the United States (20). Bolded figures are reported directly in sources and unbolded figures are estimated by proxy, using a scaling of 0.48 W/lb cotton year, taken from 1870 data.

Year	Avg. Dom. Con. (M lb)	Water Power (MW)	W/lb cotton
1790	**2.5**	1.2	0.480
1800	**19.4**	9.3	0.480
1810	**37.3**	17.9	0.480
1820	**59.2**	28.4	0.480
1830	**105.6**	50.6	0.480
1840	**179.4**	86.1	0.480
1850	**390.8**	187.4	0.480
1860	**644.5**	309.1	0.480
1870	**702.8**	**337.2**	**0.480**
1880	**1056.2**	**365.5**	**0.346**
1890	**1392.0**	**374.4**	**0.269**

7.9. Wind Power, Mechanical.

7.9.1. Sailing Ships. Sailing vessel power usage is derived by multiplying tonnage of commercial vessels (from HSUS (6)) with a fixed estimate of power usage per tonnage: 80 W/T, taken from Schurr and Netschert (5) who estimate this quantity for sailing ships of the mid-19th century. Results are given in Table S19. The tonnage estimates omit recreational boats. Estimated U.S. sailing tonnage declines almost monotonically from 1860 until records of commercial vessels cease in the 1970s.

We assume a constant scaling factor for all vessels as the use of energy by a sailing vessel is nontrivial to estimate. The efficiency of the vessel as a whole varies according to the hydrodynamicity of the hull, the speed of the ship, and other factors. Sailing vessels changed greatly over historical time, less so in the period we study, but ship design did rise in efficiency over time. For this reason we are likely underestimating wind energy for sailships in the early 19th century and overestimating it in the 20th century.

Table S19. Sailing ship tonnage and estimated Wattage required, 1800–1980. We index sailing vessel energy requirements to their tonnage from (6), using a conversion factor of 80 W/T. As with all non-thermal renewables we assume an efficiency of 1; see Section 6.2.2).

Year	Sailing Tonnage (kT)	MW Inferred
1800	**972**	77.8
1810	**1424**	113.9
1820	**1258**	100.6
1830	**1127**	90.2
1840	**1978**	158.2
1850	**3010**	240.8
1860	**4486**	358.9
1870	**2363**	189.0
1880	**2366**	189.3
1890	**2109**	168.7
1900	**1885**	150.8
1910	**1655**	132.4
1920	**1272**	101.8
1930	**757**	60.6
1940	**200**	16.0
1950	**82**	6.6
1960	**23**	1.8
1970	**16**	1.3
1980	**0**	0.0

7.9.2. Wind Pumps. Sales of windmill pumps rose spectacularly in the 1860s, 70s, and 80s with the encroachment of U.S. settlers into the dry West, and total windmills are estimated to peak at 6 million pumps in 1920 (31). Estimates after 1900 are less certain. We have assumed that roughly half of these pumps went into disuse by midcentury, and that their use then held steady at 3 million pumps until the present (130). Future work on wind power might explore the persistence of these pumps on the Great Plains, where they are still used to water livestock. Table S20 shows the resulting estimated number of agricultural windmills operational in each decade. All wind pumps are assigned to the agricultural sector.

For power per windmill, we take a mid-range estimate of reported Wattage figures for various windmill models (130). We assume farm windmills used for pumping water generate roughly 65 W of power when turning and operate about 8 hours a day, for a mean power of 21.7 W. As with all non-thermal renewables, we assign an efficiency of 1.

Table S20. Wind power in pumping water for agriculture, estimated, 1860–1960. The rise of wind pump to a peak of 6M in 1920 is well-attested; the decline afterwards is a rough estimate (31). We assume wind pumps generate 65 Watts of power and operate 8 hours/day (130), and that absolute power from windmills is constant from 1960 onwards.

Year	Wind pumps (M)	MW
1860	0	0
1870	0.3	7
1880	1.0	20
1890	3.0	65
1900	4.0	90
1910	5.5	120
1920	6.0	130
1930	5.5	120
1940	4.0	90
1950	3.5	75
1960	3.0	65

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7.10. Natural Gas. The beginning of the natural gas industry in the United States is typically taken as 1884, when a pipeline was built to carry gas 18 miles to Pittsburgh from the Haymaker well in Murrysville, PA (5, 131). Gas use in the U.S. began far earlier, though, via manufactured gas ('town gas') distilled from organic materials. In 1817, Baltimore streets were lit with gas made from pine tar. New York City followed in 1825, Boston in 1829, and Philadelphia in 1836 (131, 132). By the 1850s, most major U.S. cities had gasworks and networks of cast-iron pipe. Natural gas was typically found accidentally, first in wells drilled for salt brine, and from the 1860s onward while drilling for oil. (The Haymaker gas field was an accidental discovery.) Poor pipeline quality meant that natural gas could be used only locally, first by only local residents (carried short distances in wooden or lead pipes) but later by large industrial customers who relocated to the gas fields (e.g. (95)). Manufactured and natural gas therefore served different customers. Most U.S. cities continued to be lit by manufactured gas through the 19th century, til pipeline improvements in the 1920s allowed transport distances to stretch to hundreds of miles (132, 133, 139). Natural gas became widely available only with the expansion of the pipeline network after WWII (133, 139).

Natural gas production values are provided by the EIA (2) since 1885, with data every 5 years til 1900 and annually thereafter. We do not attempt to estimate natural gas use in previous decades, but simply interpolate between an assumed zero usage in 1880 to the reported ∼50 W/cap. in 1885. Manufactured gas, which was predominantly made from coal from the mid-19th century, appears in our inventory as part of the coal fuel stream. (See Section 3.3 for discussion.)

We allocate total natural gas to individual sectors using the estimates of Schurr and Netschert, who provide sectoral shares every 5 years from 1905 (5). For all earlier years, we assign the 1905 sectoral shares, with one exception: electricity production. Use of natural gas for electricity generation was uncommon and likely occurred largely on industrial sites where gas was used in other contexts. Early natural-gas fired generation almost certainly occurred via boilers and steam turbines; the first gas turbine for power generation in the U.S. was installed only in 1949. Schurr and Netschert estimate that 4% of *industrial* natural gas (rather than the share of *all* natural gas) was used for electricity generation in 1920. Before 1920, they include electricity generation under industrial use. We assume that 0% of natural gas was used in electrical generation in 1900, rising to 4% of industrial use by 1910. Results are shown in Table S21.

Table S21. Natural gas, 1885–1930. Bolded values are given directly in sources (2, 5), and unbolded are extrapolated as described in text. All values in billions of cubic feet.

Year	Total	Residential	Commercial	Ind. (incl. elec.)	Elect. Gen.	Ind. (no Elect.)
1885	**76**	17	6	53		
1890	**239**	53	19	167		
1895	**137**	30	11	96		
1900	**236**	52	19	165		
1905	**389**	83	28	**278**	6	272
1910	**509**	128	42	**339**	14	325
1915	**629**	163	54	**411**	16	395
1920	**812**	214	72	**512**	**22**	**490**
1925	**1210**	204	68	**916**	**46**	**870**
1930	**1979**	**296**	**81**	**1565**	**120**	**1445**

7.11. Petroleum. Petroleum production in the U.S. began in 1859, with the successful drilling of a producing well at Oil Creek in Titusville, Pennsylvania. (Some collection of petroleum from oil seeps occurred in earlier years, but this is not relevant for our inventory as it was primarily sold to apothecaries and used as medicine rather than as an energy source.) Unlike other fuels, crude oil was documented throughout its history, and the EIA provides annual production numbers from 1860, as well as imports and exports. The petroleum timeseries is complicated by a large and complex international trade in crude oil and refined products, and by the fact that in the standard accounting, the petroleum fuel stream includes natural gas liquids (NGLs, including ethane, propane, butane, and pentane) derived during processing of "wet" natural gas. The EIA provides domestic total petroleum consumption values from 1949 (2), but some choices must be made for pre-1949 years.

International trade in oil began almost immediately, with the U.S. shipping barrels of oil to Europe in 1879 (131). Exports reached 9% of U.S. production in 1885, but dropped as domestic usage expanded. By the late 1940s, the U.S. was a net importer of petroleum and remained so for over 70 years. (The fracking revolution of the 2000s means that the U.S. may again become a net petroleum exporter in 2020.) We cannot however simply use the EIA's estimates of early domestic crude oil production (+ imports − exports), since the timeseries does not match up with the consumption estimates beginning in 1949: the discrepancy is -9% of total consumption, presumably because of import of refined products, which are not well tracked. We therefore combine several data sources to construct an 1860–1949 annual timeseries of U.S. petroleum consumption. We use the well-sourced consumption estimates of Schurr and Nestert (5), which are at 5-year intervals, and scale them in intervening years using EIA domestic crude production (2). The resulting timeseries matches well with the EIA's 5-yearly historical *EIA2012* dataset (32), which we consider insufficiently documented to use directly (Figure S22).

The main complication with tracking U.S. petroleum is allocating it by sector. Schurr and Netschert provide sectoral usage from 1925, but earlier years must be estimated, and we also must disaggregate the agricultural sector from the broader

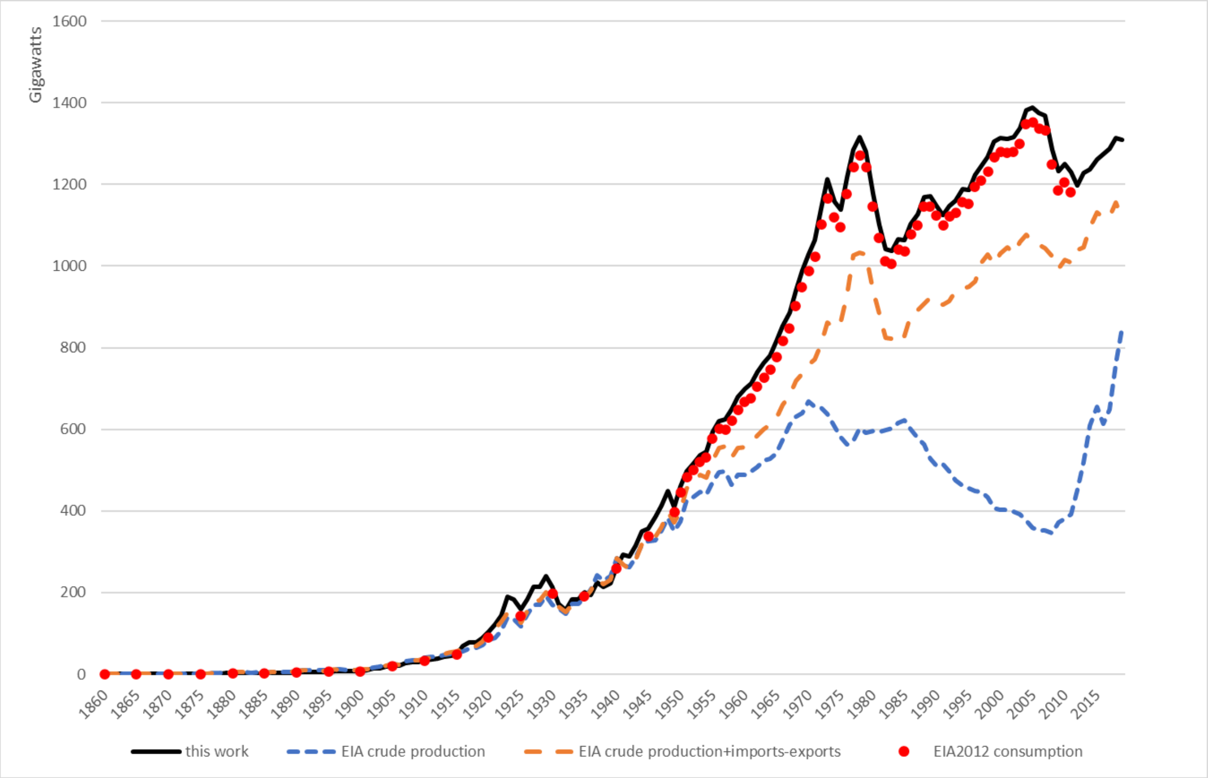

Fig. S22. Comparison of annual petroleum timeseries, 1860–2019. The composite we use (black) is EIA domestic consumption from 1949 onwards; for the 1860–1949 period we take semidecadal consumption numbers from Schurr and Netschert (5) and interpolate annual data based on the EIA's annual crude oil production series (2). For comparison we show the *EIA2012* (32) historical consumption estimate (red dots); discrepancies may be due to its rounding. We also show EIA crude production (blue dashed), and crude production corrected for imports and exports (orange dashed). The difference between between black and orange dashed lines involves some correction for import/export of refined products and the contribution of natural gas liquids to the petroleum fuel stream. Note the sharp rise in U.S. crude production after ∼2007, when modern fracking techniques allowed production from shale gas. The U.S. is projected to become a net exporter of petroleum in the year 2020, for the first time in ∼75 years.

"industrial" category. Since nearly all end use is as distillate products such as gasoline rather than as crude oil, the first step is to apportion crude production into refined products. We construct timeseries of four individual refined products – kerosene, gasoline, diesel, and fuel oil, which collectively account for ∼85% of petroleum consumption today (2)[12] – using data from the *Historical Statistics of the United States* (HSUS). Kerosene and gasoline were tracked already in 1875, and fuel oil in 1880, but diesel and other refined products appeared in government reports only in 1935. In some cases we extend the record earlier by scaling by various proxies (e.g. we estimate pre-1935 diesel usage in transportation based on reported tonnage of diesel-powered ships). The remainder of oil production is allocated to industry. This category includes unrefined crude oil, refinery losses, and products consumed as feedstocks in manufacturing rather than as fuels. In the earliest years, it also includes outright wastage, as the main marketed product was kerosene and refiners simply dumped up to 20% of the original volume of oil (5). We assign this wastage to industry on the argument that it represents operational use of crude in the refining sector. Wastage diminished quickly as more uses for petroleum products were found. By 1915, only 2.4% of crude was lost, and by 1920, the oil industry had matured to its modern practice of near-complete utilization of crude (5).

We then allocate those products to individual sectors. Records of sectoral uses of petroleum products begin with the 1925 Census (1), which tracks use of fuel oil, kerosene, gasoline, and diesel in approximately 20 sub-sectors; these were aggregated by Schurr and Netschert (5). For pre-1925 years, we allocate petroleum products to sectors based on proxy data, or we hold the 1925 share constant. Individual products are discussed below and their allocations shown in Tables S22–S24. Final summary results for the whole petroleum fuel stream from 1860–1955 were shown in Table S6 and Figure S20 above.

Kerosene: The motivation for the initial development of the U.S. oil industry was to produce kerosene for residential lighting (28, 29). Kerosene was therefore tracked early in HSUS statistics, from 1875. Sectoral use of kerosene was recorded from 1920 onward, but in the earliest years it is overwhelmingly used in households (99.7% in 1920 and 99.9% in 1930), with the remainder in industry (5). We apply 1920 sectoral shares to all pre-1920 years. Because of this residential dominance we do not include a table of kerosene use here.

Gasoline: Gasoline, a lighter and more volatile hydrocarbon than kerosene, was originally considered a useless byproduct of kerosene distillation. Although gasoline production is reported from 1875 (5), it found its major market only in the 1890s with the development of the internal combustion engine and the automobile. By the 1910s, petroleum engineers were working to

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[12] Counting "kerosene-type jet fuel" (4.41% of the total) as kerosene; otherwise closer to 80%.

develop thermal cracking to produce gasoline from kerosene. Gasoline is now the primary transportation fuel, and virtually all of modern gasoline use is by the transportation sector, where it powers cars, motorcycles, light-duty trucks, boats, and small aircraft. Minor non-transportation uses include portable power tools (chainsaws, blowers, etc.) and some emergency generators.

Prior to 1900, when the number of automobiles was very small, we assign all gasoline to industry, where it is used as a solvent and as e.g. an ingredient in paints (29). The total number of U.S. registered vehicles was only ∼8000 in 1900 (of which ∼3000 were electric), but rose to 23 million by 1920 (6). By 1925, when the first use statistics were assembled, more than 95% of gasoline was used in transportation (5). For the 1900–1925 period, we construct separate estimates of gasoline use in transportation and agriculture, and assign all remaining gasoline to industry. These estimates are described below, and the resulting gasoline use by sector is shown in Table S22.

For transportation, we scale gasoline from 1900–1925 use by the number of non-electric motor vehicles registered in the United States. Registered motor vehicles were tracked in HSUS since 1900 (6) and Netschert and Schurr report their gasoline usage from 1925 (5); we use a scaling factor of 594 gal/car/yr from the combined 1925 values. In some early years we must apply a correction for vehicles not using gasoline, since early automotive technologies were quite diverse and electric cars were initially very popular. We have only one reliable estimate of electric car numbers, the 1900 Census Report on Manufactures, part IV "Electrical Apparatus and Supplies", which surveyed all equipment using electricity in the U.S. and reported that the majority of new cars and ∼1/3 of all existing cars were electric. In 1900, a total of 109 different U.S. automobile manufacturers produced 4,192 new vehicles, of which 1,575 were powered by electric motors, 1,681 by steam engines, and only 936 by gasoline-burning internal combustion engines (6, 140). The era of diversity was short: in just five years the number of cars increased tenfold, virtually all gasoline-powered, and nearly all manufacturers of non-gasoline vehicles shut down (140). We therefore correct for electric vehicles only between 1900 and 1905, assuming their numbers fall linearly to zero. We do not attempt to separately treat external-combustion steam cars as they typically fired their boilers with some petroleum product, often kerosene or gasoline or a mixture of both (140). Note that gasoline was not used in trains (55), since the gasoline engine does not provide sufficient torque for a vehicle as heavy as a train. Locomotives used petroleum first as fuel oil burnt to fire steam engine boilers, and then as diesel with the adoption of diesel-electric transmissions. Railroads therefore appear in Tables S23 and S24 below.

For agriculture, we must construct a separate estimate of gasoline use for the entire 1900–1940 period, since tractor fuel use was not separately reported in government statistics before 1940. To develop a scaling factor, we use figures from the Agricultural Census of 1954 (3), which collected statistics on gasoline and diesel use by tractors and farm equipment from 1935 onward. We use a value of 757/gallons/year per tractor from 1940, and take estimated numbers of tractors from Olmstead and Rhode, *Creating Abundance* (2008) (37). We assume that all tractor fuel before 1940 was gasoline: the diesel engine was used in farm equipment only later, after fuel use in agriculture is fully tracked.

Table S22. Gasoline, 1875–1945. Fuel totals are given in units of millions of gallons per year. Note that the convention for gasoline differs from that of other petroleum products, which are usually denoted in barrels. Prior to 1900, when the number of automobiles was very small, we assign all gasoline to industry (29). Before reliable statistics on gasoline use by motor vehicles (which begin in 1925), we scale transportation use based on the total number of automobiles registered in the U.S. from HSUS (6) with a factor of 594 gal/year/vehicle derived from 1925 usage in (5). Note that we correct vehicle numbers in 1900 for an assumed 1/3 of total registered automobiles that were electric (140); see text. We scale gasoline use in agricultural vehicles based on the number of farm tractors employed in the United States, from (37), with a factor of 757 gal/year/tractor, derived from 1940 fuel use from the Agricultural Census (3).

year	total	ag.	ind.	trans.	tractors	automobiles	trucks	buses	aviation	tractors (no.)	automobiles (no.)
1875	**47**	-	47	-	-	-	-	-	-	-	-
1880	**78**	-	78	-	-	-	-	-	-	-	-
1885	32	-	32	-	-	-	-	-	-	-	-
1890	**202**	-	202	-	-	-	-	-	-	-	-
1895	217	-	217	-	-	-	-	-	-	-	-
1900	**344**	-	341	3	-	-	-	-	-	-	5000
1905	**357**	-	310	46	-	-	-	-	-	-	**77400**
1910	**667**	-	394	273	-	-	-	-	-	**1000**	**458377**
1915	**1780**	18	391	1389	-	-	-	-	-	**25000**	**2332426**
1920	**5178**	52	335	4843	-	-	-	-	-	**246000**	**8131522**
1925	**11338**	231	926	**10412**	-	**8460**	**1810**	**142**	-	**549000**	**17481001**
1930	**19791**	612	1630	**18161**	-	**14758**	**2946**	**457**	-	**920000**	**23034753**
1935	**21797**	674	1435	**20361**	-	**16253**	**3553**	**410**	**145**	**1048000**	**22567827**
1940	**29277**	**1187**	**906**	**28371**	**1187**	**22035**	**5646**	**571**	**119**	**1567000**	**27465826**
1945	**33833**	**2153**	**1116**	**32717**	**2153**	**19627**	**5926**	**800**	**6364**	**2354000**	**25796985**

Diesel: Diesel fuel is less volatile than gasoline and was developed for use in compression-ignition Diesel-cycle engines, which obtain higher efficiencies and typically higher torques than gasoline-powered Otto-cycle engines. The diesel engine was invented as a replacement for the stationary steam engine, but soon found use in the transportation sector for powering heavy vehicles, first ships and later trucks and farm equipment. In the 1930s-50s, locomotives converted to diesel-electric transmissions (diesel engines driving generators that power electric motors). Diesel engines are also used today in large emergency or portable electricity generators, and their fuel economy means that diesel also plays a minor role as a fuel for U.S. passenger vehicles.

Diesel was not accounted for in national statistics until 1935, making its early use difficult to track. Before this point, diesel was simply grouped with other distillates under the broad term "Fuel Oil". We do not attempt to disaggregate diesel generally, but do estimate its use in ships from 1925–1935 since HSUS tabulates the gross tonnage (GT) of ships burning diesel from 1920 onwards (6). We scale the use of diesel as ship fuel by assuming a constant factor of 34 bbl/year per GT before 1935, derived from 1935 values. Resulting usage is shown in Table S23.

Table S23. Diesel, 1925–1945. Fuel totals are given in thousands of barrels. Diesel is tracked in national statistics only from 1935; earlier it was grouped with other distillates under "Fuel oil". Sub-sectoral uses are tracked from 1940; we show those here for informational purposes. We estimate use in ships from 1925–1935 by scaling to reported tonnage of diesel-powered ships (6) using a scaling factor of 34 bbl/GT/yr.

year	ag.	ind.	trans.	elec.	ind.	oil comp.	railroads	ships	military	misc.
1925	-	-	3024	-	-	-	-	3024	-	-
1930	-	-	8514	-	-	-	-	8514	-	-
1935	**162**	**5998**	**10014**	-	-	-	-	**10014**	-	-
1940	**246**	**4173**	**18619**	**1631**	**1957**	**223**	**1838**	**12979**	**1115**	**4926**
1945	**437**	**9786**	**53122**	**3067**	**6025**	**229**	**12036**	**13374**	**22950**	**8731**

Fuel Oil: "Fuel oil" is a broad category of liquid petroleum products consisting of long-chain, low-volatility hydrocarbons. The term is often used to describe the heaviest and most viscous liquid fuels, but has been interpreted broadly enough to include diesel. Some fuel oils are "residual", i.e. they are liquids that remain after distillation of lighter and more commercially valuable products (29). The heaviest fuel oils are not suitable for internal combustion engines but are burnt only for heating buildings or boilers (for steam heat or steam engines).

Fuel oil production is reported in HSUS from 1880 (6). We assume the earliest consumption was purely in industry, but fuel oil soon found a role in transportation as a replacement for coal in external-combustion steam engines (29, 55). Liquid oil had many advances over coal: it is more energy dense, cleaner burning, easier to transport and store, and less labor-intensive to supply to the boiler (98). (For the largest locomotives, fuel oil became a necessity since human "stokers" could not shovel coal fast enough to keep them powered.) Oil use in locomotives is reported in the U.S.G.S. Report on Mineral Resources (84) from 1900, though only a limited number of railroads were converted. See Note 7.3 for details of our estimate. Ocean-going steamships began experimenting with fuel oil later but converted faster and more completely. Before WWI, Zimmerman estimates that only 1% of the global steamship tonnage was oil-powered (103), but use expanded rapidly in the war years (101) and by 1919, nearly half the U.S. fleet used oil (103). Data on fuel oil use in steamships appears in HSUS only after 1920, when it was already important. We assume the proportion using fuel oil expanded linearly from 1905–1920. See also Note 7.4.

Fuel oil was also used in household heating and for electricity generation very early; both uses are already significant when HSUS first reports data in 1925. For heating, we assume that the share of fuel oil used increased linearly from 0 in 1890 to the reported 8% in 1925. For electricity generation, we similarly assume a linear rise in fuel oil share from 0 in 1890 to 9% in 1910 and then holding steady until 1925. Resulting estimates of fuel oil use by sector are shown in Table S24.

Table S24. Fuel oil, 1880–1945. Fuel totals are given in thousands of barrels. We allocate all fuel oil before 1900 to industry. We estimate fuel oil for residential/commercial heating and electricity generation by interpolating between 0 usage in 1890 to their first reported values in 1925. (See text.) Fuel oil use in ships is interpolated from 0 usage in 1905 to first reported values in 1920.

year	total	res./com.	trans.	elec. gen.	res./com. heating	mining/manuf.	oil comp.	railroads	vessels	military	misc.
1880	**500**	-	-	-	-	-	-	-	-	-	-
1885	208	-	-	-	-	-	-	-	-	-	-
1890	**1400**	-	-	-	-	-	-	-	-	-	-
1895	1508	-	-	75	-	-	-	-	-	-	-
1900	**7300**	1736	**357**	365	-	-	-	**357**	-	-	-
1905	**8600**	3065	**476**	430	-	-	-	**476**	-	-	-
1910	**40500**	5412	24991	4050	-	-	-	**22001**	2989	-	-
1915	**88800**	9558	52325	8880	-	-	-	**43527**	8798	-	-
1920	**211000**	16879	**82111**	32151	-	-	-	**55580**	**26531**	-	-
1925	**365000**	**29807**	**158534**	**33652**	**22779**	**69336**	**48701**	**72218**	**79288**	-	**14056**
1930	**372500**	**52638**	**171966**	**26749**	**42703**	**59379**	**53437**	**67900**	**94131**	-	**19869**
1935	**360100**	**88634**	**142013**	**23647**	**76853**	**63576**	**48116**	**55651**	**74581**	-	**23561**
1940	**499500**	**175766**	**143471**	**31164**	**160379**	**71983**	**51705**	**66260**	**61824**	-	**30774**
1945	**718700**	**175604**	**341516**	**38289**	**165216**	**104222**	**58235**	**114719**	**101121**	**104901**	**20775**

Unrefined/Other Petroleum Products: Other petroleum products are tracked in HSUS after 1920. We assign all these to industry, including unrefined crude burned at the point of production (29) and residues that were discarded as waste in the early years of the industry. Note that this category includes asphalt (bitumen) and other heavy residues used in road surfacing, which should properly be assigned to transportation. In 2019, asphalt and road oil production was equivalent to 3% of crude oil volume (2).

7.12. Electricity. The beginnings of the electricity industry are poorly documented. The first U.S. electricity sales occurred in 1882 with two projects of Thomas Edison's (a hydroelectric plant in Appleton, WI and the famous Pearl Street coal-fired generating station in lower Manhattan), but electricity does not appear regularly in government statistics until almost four decades later. Between 1882 and 1920, records are scarce. Electricity production was decentralized, and much of it involved municipalities or industrial facilities generating power for their own use, leaving no record of sales to customers. Detailed reporting is available only from 1920 onwards, when the *Historical Statistics of the United States* records total electricity generated, its sectoral usage, the proportion of the total that is marketed vs. privately generated, and the combustion fuels burnt to produce it.

To estimate electricity's role in the U.S. energy system between 1882–1920, we follow a series of four steps. We 1) estimate the total consumption of electricity, which involves separate estimates for individual sectors, 2) identify what portion of the total is produced by hydroelectric plants, and 3) for electricity produced via heat engines, estimate a thermal efficiency. This information then yields the total primary energy required for electricity generation. (Note that we do not attempt to identify differing proportions of hydropower vs. thermal generation by sector, but instead aggregate all electricity. In reality, grid connections were limited and proportions likely differed.) Finally, 4) we estimate the share of the different combustion fuels used in thermal electricity generation. While all thermal power plants at this time used external-combustion steam engines or turbines, the boilers that produced steam could be fired by any of coal, oil, or natural gas. These steps are described below, and results are shown in Table S25.

1) Electricity consumption by sector. Government statistics on electricity consumption in the U.S. before 1920 are extremely limited. HSUS provides some records in 1912 and 1917, noting total electricity consumption by residential, commercial, industrial, municipal, and transport sectors, and the overall proportion of marketed electricity sold to customers vs. non-marketed electricity generated on-site. However, earlier information is provided by electricity trade journals, which arose almost immediately to report on the growing industry: *Electrical World* was first published in 1883 and *The Electrical Engineer* in 1888. Our primary record of U.S. electricity production before 1900 is a 1922 trade article (Huey, "Electrical development the key to prosperity", *Electr. World* 80, 545–546, 1922, henceforth *EW*) (128) which reports marketed electricity in individual sectors at 5-year intervals from 1887 to 1912 and then semiannually or annually to 1920; the 1912 and 1917 totals duplicate HSUS values. Usage is divided into categories of "industry", "lighting" (left ambiguous as to its purpose or sector), "electric railways", and "line losses". For marketed electricity, we treat line losses in the same way as we do the waste heat of thermal generation, i.e. we apportion them by sector.[13] For non-marketed power, we assume zero line losses since all generation is on-site.

For *industrial electricity*, we use the *EW* values for marketed power, and estimate non-marketed power based on data from the Census *Report on Manufacturers* of 1910 and 1920. These volumes include a report on electrical equipment in factories that gives the total horsepower of all industrial electric motors for selected years from 1889, as well as the fraction of those motors powered by on-site generators vs. by electricity "rented" (purchased) from utility companies (1). That information alone is not enough for us to derive industrial electricity consumption, since we do not know the efficiency of the motors nor the fraction of time they are in operation, and industrial facilities also used some electricity for lighting. We therefore use the Census data to scale *EW* data to account for non-marketed contributions, i.e. we divide *EW* industrial values by the fraction of industrial motors that used marketed electricity (∼30-60%, rising over time). This scaling is broadly consistent with the breakdown of *total* electricity from HSUS, which reports 41% marketed in 1912 and 44% in 1917 (6)[14]

For *transportation* and *residential/commercial electricity*, the *EW* sectoral divisions are not sufficient, since their lighting category includes both households and streetlights, which we would assign to transportation. Residential/commercial electricity use is therefore less than the lighting value reported in *EW*. On the other hand, transportation usage is considerably larger than *EW* railways, both because of street lighting and because much municipal electricity was generated in-house rather than purchased. We therefore benchmark all transportation use to the 1912 HSUS value, and use *EW* only to estimate a general timeline of growth. That is, for each year i we estimate transportation electricity as $\mathrm{HSUS}_{1912\ \mathrm{trans.}} \times (EW_{light.} + EW_{rail.})_i / (EW_{light.} + EW_{rail.})_{1912}$. For residential/commercial, we assume there is no non-marketed generation, and similarly scale it using the timeline of growth given by *EW* lighting.

For completeness, we also construct an estimate of electricity use in 1882 from Edison's two projects, using their rated capacity and assumed times of operation. (Both provided electricity only for lighting.) For the 600 kW Pearl Street plant, which served residential/commmercial customers, Edison's financial projections assume 5 hours of operation per day (134, 135). For the 12.5 kW Vulcan Street hydroelectric plant in Appleton, which served industrial customers, we assume 5 hours/day (129). In both cases we pro-rate for the fraction of 1882 that the plants were operational (4 and 3 months, respectively.)

Our final values for early generation appear consistent with the previous estimates. Values between 1902–1917 are slightly higher than those of Neill (1942) (141) (on average $\sim +10\%$), but with considerable scatter ($\sigma = 12\%$).

2) Hydroelectricity. We derive hydroelectric power before 1920 using data from Schurr and Netschert, who tracked the capacity of U.S. hydroelectric dams back to the 1880s and estimated their electricity output (5). Results imply that hydro provided 36–50% of electricity in the pre-1920 period. Note that the EIA has published an estimate of early hydroelectricity in their *EIA2012* dataset (32), but it appears inflated by application of an unknown assumed efficiency. For example, in 1900

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[13] Line losses were high in the first decades of the electricity industry, at 25% in 1890 and 18% in 1920, as opposed to about 5% today for transmission over much longer distances (EIA estimate (2)). A significant portion of early U.S. generation was DC, which required lower voltages and therefore incurred high losses, and even AC transmission voltages were low relative to those used today. In 1897, over 60% of U.S. generating capacity was still DC and the maximum transmission voltages even for AC were only ∼30 kV (141).

[14] Combining the HSUS 1912 total industrial electricity with Census values for installed industrial motor horsepower and a ∼40% share of motors using marketed electricity yields a scaling of 216 W industrial electricity per hp electric motors installed, i.e. a ratio of 0.29.

Schurr and Netschert report 346 MW of hydroelectricity produced, while *EIA2012* reports 8.37 GW. We assume that the *EIA2012* values are inflated by dividing by an assumed efficiency to make primary hydropower appear more analogous to thermal generation; *EIA2012* values would be consistent with ours given an applied efficiency of 4% in 1900. For clarity and consistency, we assign hydroelectricity an efficiency of 1; see Section 6.2.2.) An assumed efficiency for *EIA2012* hydropower would have to be dynamic over time and is completely undocumented, making interpretation confusing.

3) Thermal generation efficiency. While basic thermodynamic constraints mean that any use of a heat engines involves some loss of energy as waste heat, the earliest thermal electricity generation was extraordinarily inefficient. The first thermal power plants used reciprocating engines (i.e. with pistons moving up and down in cylinders) connected to generators (dynamos) by leather belts (40, 127). Mechanical losses in the belt drives contributed to abysmal efficiencies.[15] We have two primary-source estimates of their magnitude. Contemporary records of coal used in Edison's Pearl Street Station give a rate of 10 pounds of coal per kW-hour electricity generated, i.e. a conversion efficiency of only 2.5% (134, 135). We use this number as our 1882 value. In 1902, when steam turbines had at least partially replaced reciprocating engines, we have a figure of 6.4 pounds of coal per kW-hour of electricity, i.e. a 4.4% efficiency, from a 1930 report written by the Brookings Institute and the U.S. Geological Survey (136). By 1920, HSUS provides both thermally-generated electricity and the amount of fuel consumed; dividing these shows that thermal generation efficiency had reached 9.6%. We interpolate linearly between these figures to construct the timeseries of rising efficiency shown in Figure S12 in Section 3.5.1. These results are broadly consistent with the historical U.S. estimates of Neill, 1942 in the *Edison Electric Institute Bulletin* (141), though slightly higher: e.g. we use 5.8% in 1907 while Neill estimates 4.6%. (The timeseries of Ayres et al., 2003 (143), constructed from data from 1907 onwards, also suggests mean thermal efficiency above 5% in 1907.) Multiplying these efficiencies by the electricity generated in thermal plants, and then adding hydropower, gives the total primary energy usage of the electric sector.

4) Fuel shares in thermal generation. While most early thermal power plants burned coal, some use of oil and natural gas did occur (134, 135). However, no official government tally of fuels burned to generate electricity was made before 1920. The only data point we have is an estimate from the 1930 Brookings/USGS report of 11 million tons of coal burned for electrical generation in 1902 (136). By 1920, when detailed HSUS statistics begin, coal accounts for 83% of thermal electricity generation, petroleum 15%, and natural gas 2% (calculated assuming that all thermal generation had the same efficiency).[16] To estimate the growth of petroleum and natural gas use in electricity generation, we interpolate from assumed times of first use (1890 and 1900, respectively) to their 1920 values. We interpolate using the metrics of fuel amounts provided by HSUS: we assume that petroleum use for electricity rose from 0 in 1890 to 6% of petroleum production in 1920, and that natural gas use for electricity rose from from 0 in 1900 to 4% of *industrial* natural gas in 1920.

Table S25. Historical electricity generation and primary fuel inputs, 1882–1920. Table shows information in five categories, in order from left to right: total electricity generated; estimated thermal efficiencies and primary energy inputs by fuel; marketed electricity from *Electrical World*; Census data on industrial motors and the fraction of industrial motors using non-marketed electricity; and estimated sectoral usage of electricity. All energy values are given in MW (i.e. both MW of electricity and MW of primary fuel energy). Motor capacity is given in horsepower; 1 hp = 745.7 W. See text for detailed discussion of sources and estimations. Bolded figures are reported directly in primary sources, and unbolded figures are estimated or interpolated. We omit years with no primary source data or where the only primary source data is hydroelectric power from Schurr and Netschert (available annually from 1890–1920). The final electricity timeseries is interoplated to annual values.

		primary energy inputs					*Electrical World*				Census		sectoral elect. use			
year	tot. gen. (MW)	hydro	coal	oil	ng	th. eff. (%)	line loss	light.	ind.	elec. rail	motor hp	non-m. frac.	r/c	ag.	ind.	tran.
1882	**0.05**	**0.001**	2	-	-	**2.5**							**0.05**	-	**0.001**	-
1887	43	14	480	-	-	3.0	**5**	**14**	**1**	**0**			35	-	3	6
1889	55	20	631	-	-	3.2					**16**		43	-	4	7
1890	60	**21**	875	-	-	3.3							47	-	5	8
1892	72	**63**	1825	5	-	3.5	**8**	**22**	**3**	**1**			55	-	7	10
1897	176	**207**	5308	38	-	3.9	**204**	**55**	**6**	**2**			138	-	14	24
1899	351	**300**	7332	53	-	4.1					**493**	**.63**	195	-	121	35
1902	**688**	**448**	**8838**	94	50	**4.4**	**74**	**112**	**69**	**11**			281	-	282	51
1904	915	**577**	11808	89	124	5.0					**1592**	**.72**	395	-	451	69
1907	**1632**	**796**	14215	308	271	5.8	**266**	**213**	**171**	**132**			565	-	705	96
1909	1726	**985**	16317	561	404	6.4					**4817**	**.64**	679	2	916	129
1912	**1962**	**1282**	19176	1047	515	7.3	**519**	**314**	**371**	**344**			**546**	**4**	**1233**	**178**
1914	2823	**1511**	21262	1480	539	7.9	**681**	**426**	**464**	**415**	**8836**	**.56**	645	6	1908	263
1915	3183	**1635**	22338	1686	571	8.1	**799**	**468**	**591**	**445**			694	7	2176	306
1916	3543	**1758**	24348	2812	680	8.4	**937**	**559**	**863**	**521**			743	9	2443	348
1917	**3911**	**1824**	25163	3516	725	8.7	**1175**	**639**	**1096**	**565**			**792**	**16**	**2711**	**391**
1918	4663	**1943**	26138	3894	664	9.0	**1297**	**650**	**1847**	**566**			884	18	3117	643
1919	5415	**2143**	28576	4809	695	9.3	**1447**	**708**	**2404**	**568**	**1632**	**.43**	975	20	3524	896
1920	**5833**	**2001**	**33134**	**6103**	**764**	**9.6**	**1597**	**784**	**2705**	**570**			**1066**	**22**	**3596**	**1149**

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[15] Edison's dynamos themselves were reasonably efficient at over 80% and possibly as much as 90% (141, 142).

[16] Thermal generation provided 66% of all electricity in 1920, with the remaining 34% from hydropower.

Agricultural electricity use. We estimate early agricultural electricity consumption separately, since it was both small and separately documented in HSUS. Agricultural electrical energy was fairly minimal in the first half of the 20th century, and appears to have been used for farmyard lighting and some electrical pumps. Large-scale use of electricity in agriculture began only in the late 20th century with the rise of industrial-scale animal husbandry.

Purchased electricity in the agricultural sector is reported by the HSUS from 1909, though the listed values are not amounts of electrical energy (kWh) but total expenditures on electricity ($). We use HSUS statistics for electrical power costs (6) to derive a timeseries of purchased agricultural electricity from 1909–1960. After 1960, we use agricultural electricity data derived from a variety of surveys, described in Section 7.13.3 below.

Non-marketed electricity in the agricultural sector must also be considered from the 1920s, because many families on the Great Plains installed small windmills or wind turbines to generate electricity for their own use. Farms and ranches were already accustomed to using wind power for mechanical pumping; see Section 7.9.2. We estimate this private generation using figures for wind turbine numbers and capacity from Righter, *Wind Energy in American History* (31). We assume that these turbines operated about 8 hours a day to produce the estimated wind electricity shown in Table S26. These figures are highly uncertain, since no aggregated records exist, early wind turbine companies were notoriously secretive about sales data, and overall market size and turbine characteristics varied considerably over this period (31, 130). Total electricity generated was however quite small: agricultural wind generation is considerably less than the already small use of windpower for mechanical pumping. (Compare values in Table S26 with those for pumps in Table S20.) The number of turbines plummeted after the expansion of the electrical grid in the 1940s and 50s, but these turbines are important in U.S. energy history for proving the demand for electrification that prompted the construction of a rural grid in the first place.

Table S26. Distributed generation of agricultural electricity by wind turbines, 1920–1960. These estimates are derived from Righter, *Wind Energy in American History* (31). Compare to values for mechanical wind pumps in Table S20.

Year	# turbines	W/turbine	Total (MW)
1920	50	100	.002
1930	3000	2000	2
1940	200000	300	20
1950	50000	300	5
1960	25000	300	3

7.13. Post-1949 notes.

The year 1949 marks the beginning of the modern regime of detailed information about U.S. energy usage. From 1949 onward, the EIA provides consistent and well-documented tables of annual energy usage from each primary energy source, with usage separated for residential, commercial, industrial, and transportation sectors (2). The only discussion needed for post-1949 values are therefore for a few cases where we augmented or modify EIA values, or where EIA estimates are incomplete or inconsistent across years (2). Note that our previous historical estimates are sufficiently consistent with EIA tables from 1949 onwards that no special adjustment is needed; discrepancies in 1949 are generally less than 5%. See Section 7.14 for discussion of the "match-up" between pre-1949 estimates and post-1949 EIA values;

7.13.1. Adjustment of EIA non-thermal renewables..

In our inventory we follow the convention of assigning an efficiency of 1 for non-thermal electricity generation (wind, solar PV, hydropower), so that the primary energy inputs equal the electricity outputs. The EIA follows a different convention, and adjusts all non-thermal electricity generation by a "fossil fuel conversion factor". That is, they book-keep non-thermal renewables by the amount of energy that *would be consumed* by a thermal power plant in the same era. Since thermal efficiencies rose by over an order of magnitude over the history of the electric sector, this convention means that e.g. hydropower primary inputs would appear over 10× larger in the 19th century for a given amount of electricity generated than they do in the 21st century, because of the evolution of a completely independent generation technology. See Section 6.2.2 for discussion. We therefore re-adjust all EIA values for non-thermal renewables, using the timeseries of their assumed fossil fuel conversion factor from 1949 to the present (2), so that the values we report are the electricity actually generated.

Note that we have one inconsistency, in that we aggregate all solar electricity, though properly we should treat solar photovoltaic (PV) differently from solar thermal (Concentrated Solar Power, or CSP) since CSP involves generating heat to drive a heat engine. The EIA does not disaggregate CSP and PV in all years; this is an issue for future research. The importance of CSP has however dropped over time. In 2010, utility-scale CSP plants provided nearly twice as much electricity as large-scale PV, but by 2019, strong growth in solar PV means that CSP now makes up only 5% of U.S. utility-scale solar (2).

7.13.2. Home generation of wind and solar.

The EIA does not attempt to track electricity generation that is not grid-connected, and even grid-connected small-scale solar generation (defined as $< 1MW$) is treated in a different timeseries and not tracked before 1990. We estimate home wind generation and assign it to agriculture, see Section 7.12; these values are small and peak in the 1940s. Small-scale solar generation on the other hand is increasing. While small relative to the entire electric sector, in 2019 it is nearly 40% as large as utility-scale generation, i.e. it makes up ∼29% of total U.S. solar electricity (2). We therefore add it to our total generation. From 1982–1990, we scale linearly from 0 in 1981 (when shipments of PVE cells to consumers began; all-scale solar generation always involves PV, as CSP facilities are always large) to the reported 1.8 GW distributed solar in 1990. After 1990, EIA tracks distributed generation by residential, commercial, and industrial consumers. Before 1990, we assign all distributed solar electricity to the residential sub-sector. Commercial generation constituted only 2% of the total in 1990, and industrial generation was negligible.

7.13.3. Agriculture, post-1949. The EIA does not track agricultural energy use separately, but includes agriculture within industry. We disaggregate agriculture from the broader industrial sector using a combination of various sources that provide estimates for different time periods. For the earliest years, we use the Agricultural Census (3), which tracked various statistics at multi-year intervals, including energy use; these statistics are available for 1954 and 1960. Between these points and the adjacent data points in our agricultural time series (1945 and 1965), we interpolate linearly. For the period 1965–2002, we use Miranowski 2005, "Energy Consumption in U.S. Agriculture" (137); for 2003–2015, data from the USDA National Agricultural Statistics Service (NASS), which provides complete coverage of all fuel streams (138), and validate using Hitaj and Suttles, 2016 (41), a report through the USDA Economic Research Service. These sources do not track the embodied energy of fertilizer or other agricultural inputs, which we show in Figure S7, using data from Cao, et al., 2018 (39).

7.14. Handling the EIA/Non-EIA Data Discontinuity, 1949. The largest discontinuity in our data occurs when our historical estimates must be joined to the annual EIA figures. Table S27 shows the discrepancy in 1950, the first year of overlap. The two data series agree on total U.S. energy use to within <1%, and largely agree on growth rates, but some substantial discrepancies exist in smaller flows, especially for electricity, which accounted for less than 3% of U.S. primary energy use in 1950. (We may assign too much usage to residential and too little to industry, by ±30%). Our overall electricity estimate is below that of the EIA by 11%, but this difference is small relative to the growth rate: the *annual* increase in electricity stayed consistently above 10% from 1945–1955. We do not attempt to reconcile these differences, but simply interpolate linearly between our aggregated data in 1945 and the 1949 EIA figures to produce a smooth timeseries. That is, we take EIA estimates beginning in 1949, for all sources except those the EIA does not track.

Table S27. Comparison of our reconstructed values for 1950 with EIA figures. Values of total U.S. energy use agree to <1%, but discrepancies can be large in some of the smaller energy flows. Categories marked with an asterisk (*) are explained in more depth in text. The EIA hydropower figure is adjusted to remove their applied "fossil fuel generation efficiency"; see Section 6.2.2. Because the EIA does not account for animal feed in their biomass figures, values for biomass here include only fuelwood to allow a consistent comparison.

Fuel	1950 (recon., MW)	1950 (EIA, MW)	(% diff.)
Wind	87.4	*	*
Water	11500	11000*	+4.5
Biomass*	42200	35300	+19.5
Coal	404000	406000	-0.49
Coal->R/C	92600	93800	-1.28
Coal->I	188000	186000	+1.07
Coal->T	50700	52300	-3.06
Coal->EG	73400	73600	-2.71
Petroleum	446000	446000	+0.0
Natural Gas	209000	200000	+4.5
Electricity	29900	33700	-11.3
Electricity->R	8240	8240	+0.0
Electricity->C	5950	7530	-26.6
Electricity->Ag	435	*	*
Electricity->I	22200	16700	+24.8
Electricity->T	750	775	-3.2
Total	1110000	1100000	+0.91

Omitted sources. The EIA does not consider wind energy before the advent of modern turbines connected to the electrical grid in 1984, thereby excluding small-scale distributed generation by farm families, wind pumps on the Great Plains, and those sailing ships still extant in 1950 (see Section 7.13.2).

Physical factors. In some cases we make slightly different physical assumptions than those the EIA uses. We assume a fixed 1037 BTU/cubic foot for the the energy content of natural gas, while the EIA uses an evolving value ranging from 1029–1037 BTU/cubic foot, i.e. up to 1% below our assumption. The EIA does not provide values for 1950, but the choice could at least partially explain the 4.5% discrepancy in natural gas. Energy density assumptions do not drive the small discrepancy in total coal usage (<0.5%), since we take our assumption of the heat content of coal from the EIA (24 million BTU/ton of bituminous coal and 25 million BTU/ton of anthracite). Most coal disagreements are likely due to slightly different definitions of sectors. The largest absolute discrepancy in Table S27 is in biomass (fuelwood), where our 1950 estimate exceeds the EIAs by 6.9 GW (19.5%). Differing assumptions about the heat content of wood contribute about 5%: we assume 21M BTU/cord while the EIA assumes 20M. The remaining difference falls well within the bounds of uncertainty in estimates of fuelwood consumption. All physical assumptions used are detailed in Section 6.2.

8. Validation

While this work represents the first systematic historical evaluation of U.S. energy use by sector, and therefore has no direct analogue in the literature, several existing datasets can provide at least partial validation. Section 7 describes the validation of individual fuel flows. In this section we compare to two prior compilations of nationwide energy use, the *EIA2012* historical dataset and the sectoral estimates of the Lawrence Livermore National Laboratory (LLNL).

8.1. EIA Estimates, pre-1949. As we derive most of our values from 1949 onward from detailed EIA tables, EIA data does not provide an independent validation for post-1949 years. For pre-1949 years, we can compare to the EIA's release of a timeseries of historical U.S. energy use by fuel from 1775–2011, which we term *EIA2012* (32). The *EIA2012* dataset has no public documentation and likely draws on some of the same primary source material as we do, but provides at least a partial "sanity check". We compare all the major fuels (wood, coal, petroleum, and natural gas) in Table S28, and individually in Figures S23–S26. Overall, the mean discrepancy between our data and *EIA2012* across all fuels and all years is -2% and maximum -13%.

Table S28. Comparison of our estimates with those of *EIA2012*, 1800–1945 (32). All values below are given in GW, and fractional differences are computed as (*EIA2012* - this work)/(this work). *EIA2012* values are italicized in headers; they are given semi-decadally to 1920 but we show only selected years where we have primary-source data. We make several adjustments to allow the comparison: 1) Since the EIA does not include animal feed in their biomass estimate, we compare to our fuel wood only; and 2) Since the EIA does not include mechanical waterpower, we compare only hydroelectricity. Note that we cannot compare hydropower directly since the *EIA2012* values appear adjusted by an unknown effective efficiency that is changing over time. Instead, we report the assumption that would be required for the two estimates to be identical, and for reference show our thermal generation efficiencies of Figure S12. For reference we also show total fuel streams for biomass, total waterpower, and windpower (sailships and windmills), inclusive of those parts omitted from *EIA2012*.

Year	Biomass	Wood	*EIA Wood*	% diff.	Coal	*EIA Coal*	% diff.	Petro.	*EIA Petro.*	% diff.	NG	*EIA NG*	% diff.
1800	19	17	16	-6.4	0.09	0	-	0	0	-	0	0	-
1810	26	23	21	-8.6	0.14	0	-	0	0	-	0	0	-
1820	35	30	28	-8.1	0.27	0	-	0	0	-	0	0	-
1830	47	41	38	-6.8	1	0	-	0	0	-	0	0	-
1840	63	54	51	-4.7	2	0	-	0	0	-	0	0	-
1850	81	72	72	-0.2	7	7	6.9	0	0	-	0	0	-
1860	103	89	88	-0.2	16	17	5.3	0.10	0.10	0.0	0	0	-
1870	113	97	97	-0.2	33	35	5.8	0.37	0.37	0.0	0	0	-
1880	127	104	95	-8.0	65	69	6.3	3	3	0.00	0	0	-
1890	118	84	84	-0.2	128	136	6.0	5	5	0.00	8	9	3.7
1900	114	70	67	-4.1	219	229	4.8	8	8	0.00	8	8	3.0
1910	123	64	59	-7.6	406	426	4.9	34	34	-0.01	18	18	2.3
1920	116	58	54	-7.6	532	519	-2.4	103	90	-13.3	28	27	-1.8
1925	105	56	51	-7.6	470	492	4.8	160	143	-10.6	41	40	-3.3
1930	94	53	49	-7.6	434	457	5.3	214	197	-7.9	67	65	-4.1
1935	86	51	47	-7.6	343	356	3.8	200	190	-5.2	66	64	-3.1
1940	78	49	45	-7.6	413	420	1.5	265	260	-1.8	92	89	-3.2
1945	69	46	42	-7.6	510	535	4.8	358	338	-5.4	135	130	-4.3

Year	Water	Wind	Hydro	*EIA Hydro*	*% eff. (imp.)*	% eff. (ours)
1800	0.01	0.08	-	-	-	-
1810	0.02	0.11	-	-	-	-
1820	0.03	0.10	-	-	-	-
1830	0.05	0.09	-	-	-	-
1840	0.09	0.16	-	-	-	-
1850	0.19	0.24	-	-	-	-
1860	0.31	0.36	-	-	-	-
1870	0.34	0.20	-	-	-	-
1880	0.37	0.21	-	-	-	-
1890	0.37	0.23	0.03	0.74	4	3
1900	0.43	0.24	0.32	8.37	4	4
1910	0.54	0.25	0.98	18.04	5	7
1920	0.53	0.23	2.14	24.71	9	10
1925	0.53	0.21	2.91	22.36	13	13
1930	0.54	0.18	4.10	25.17	16	19
1935	0.55	0.15	4.88	26.98	18	20
1940	0.56	0.12	5.72	29.46	19	16
1945	0.57	0.11	9.67	48.27	20	18

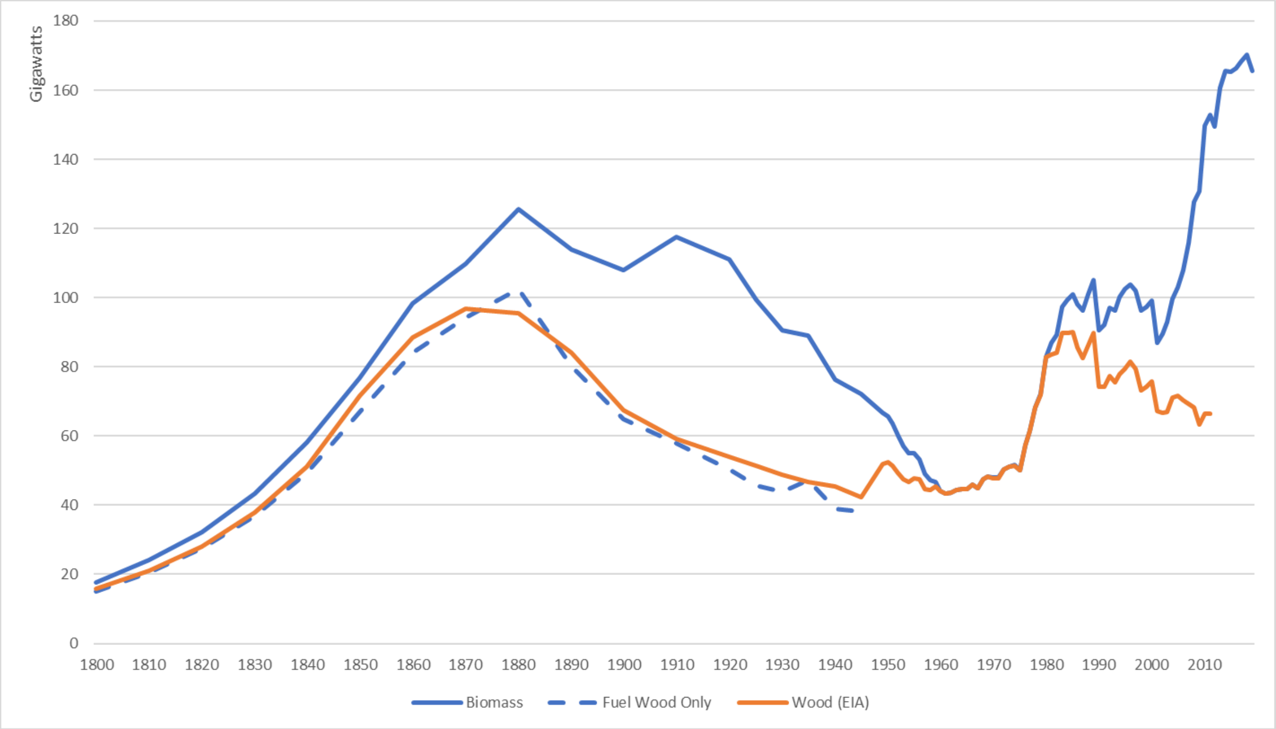

Fig. S23. Comparison of biomass estimates 1800–2019, total U.S. consumption in GW, showing our total biomass (blue solid), wood only (blue dashed, to 1949) and $EIA2012$ wood (orange) (32). The mean difference between fuelwood estimates is 5.6% and maximum -8.6% in 1810, with $EIA2012$ generally higher. Biomass estimates are significantly higher than $EIA2012\ wood$. In the early 20th century, animal feed and fuelwood are comparable in scale, underscoring how important the inclusion of animal feed is. From the 1980s onward, the difference is largely due to ethanol, which is included in our biomass fuel stream but absent from $EIA2012$.

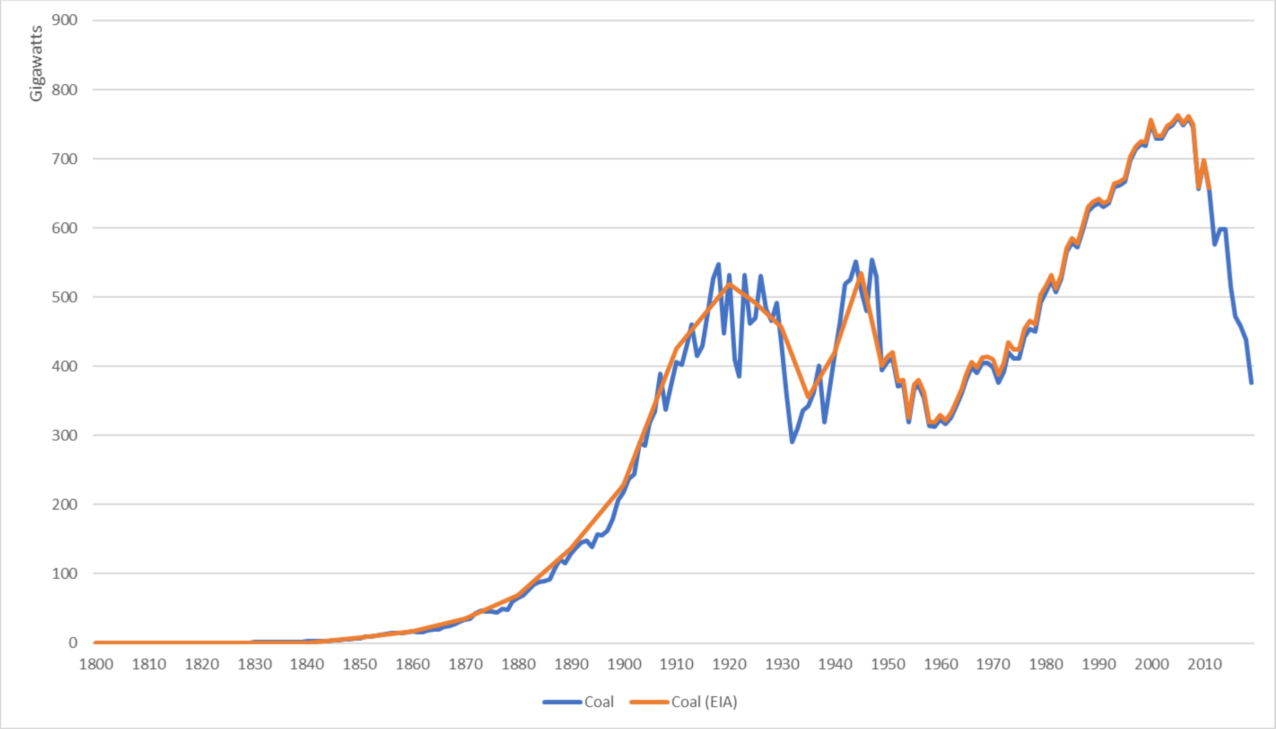

Fig. S24. Comparison of coal estimates 1800–2019, total U.S. consumption in GW, showing this work (blue solid), and $EIA2012$ (orange) (32). The $EIA2012$ timeseries is semi-decadal to 1949 and cannot capture the volatility of coal production (because of instability in the 1910s-20s, the Great Depression of the 1930s, and the effects of WWII in the 1940s). After 1949, data are annual. The mean difference between estimates is 3.4% and maximum -6.8% in 1945.

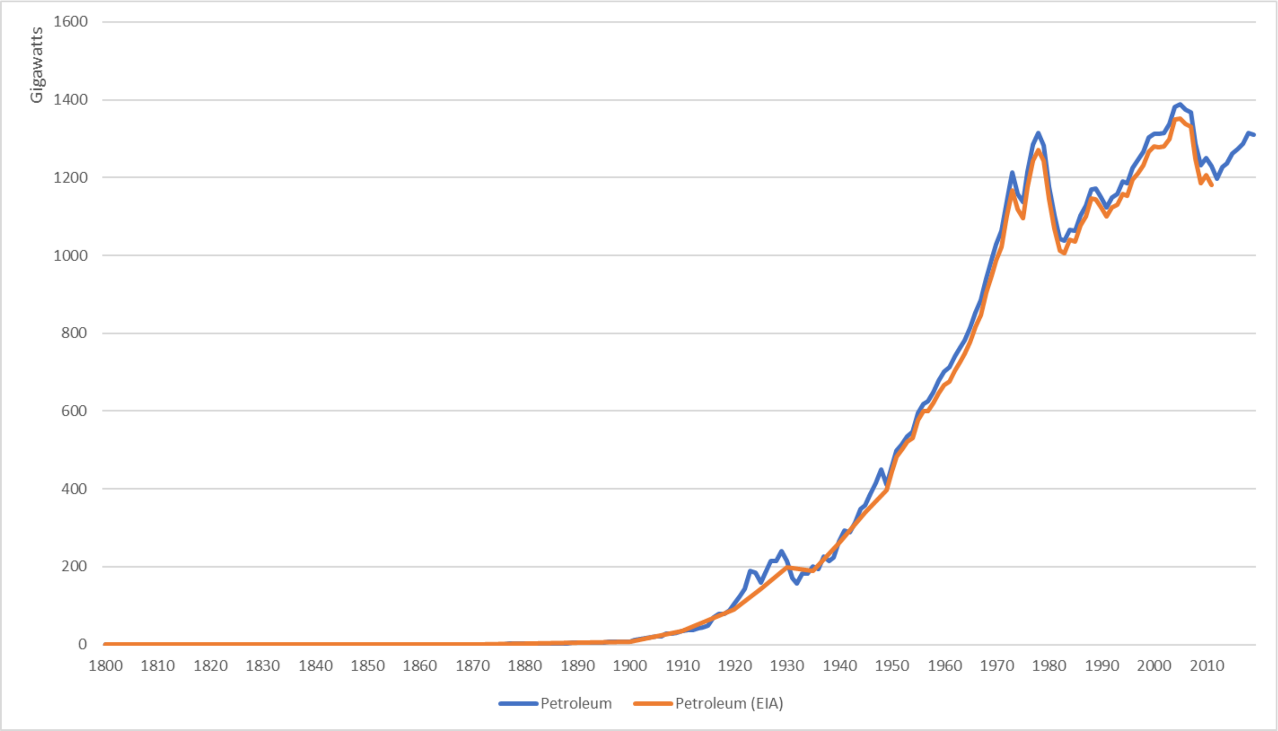

Fig. S25. Comparison of petroleum estimates 1800–2019, total U.S. consumption in GW, showing this work (blue solid), and $EIA2012$ (orange) (32). The $EIA2012$ timeseries is semidecadal to 1949 and cannot capture the boom in the 1920s followed by the Great Depression. The mean difference between estimates is -2.6%, with a maximum of -13.3% in 1920.

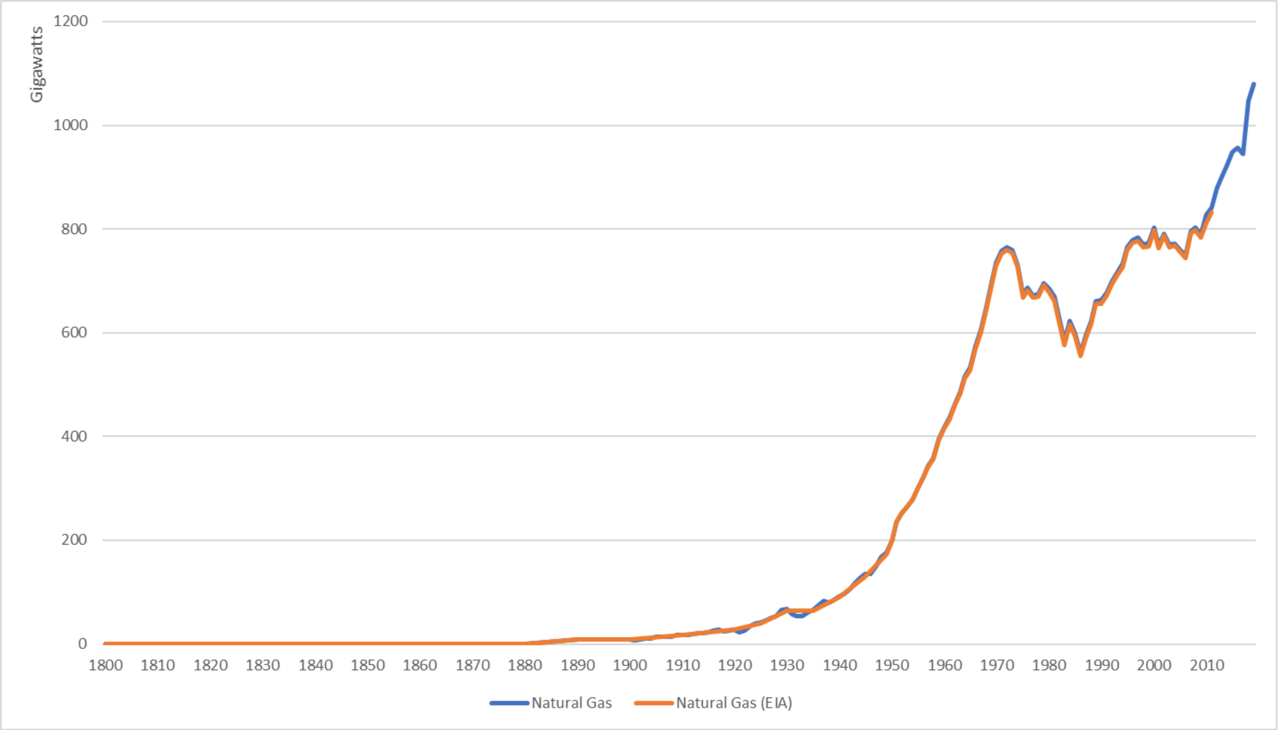

Fig. S26. Comparison of natural gas estimates 1800–2019, total U.S. consumption in GW, showing this work (blue solid), and $EIA2012$ (orange) (32). Estimates are very similar, with any minor differences explained by differing assumptions about energy density. The mean difference between estimates is -0.6%, with a maximum of -4.3% in 1945.

8.2. Lawrence Livermore National Laboratory Sankey Diagrams. The Lawrence Livermore National Laboratory (LLNL) has for many years compiled estimates of U.S. energy use by sector, using some combination of data from the EIA and data collected by the Bureau of Mines. The exact sources are poorly documented, but we assume LLNL datasets serve as a semi-independent point of comparison. LLNL energy flows are reported as Sankey diagrams and available in a variety of agency reports for 1950, 1960, 1970, 1976, and 1978 (8) and annually thereafter for all years except 1993 (7). We compare four energy flows in Figure S27: electricity generation and usage by the residential/commercial, industrial, and transportation sectors. Like the EIA, LLNL applies a time-varying effective efficiency adjustment to non-thermal electricity generation, but unlike the EIA the values are not published. For the purposes of a rough comparison, we use the EIA's values here. Across all fuel-sector streams (individual lines in a Sankey), mean discrepancy between our data and LLNL is +3% and maximum +17%. The largest discrepancies occur from 1978 to the early 1980s, when LLNL industry values are systematically below ours and LLNL residential/commercial is noisier. Since LLNL does not publish sectoral definitions, it is possible that these discrepancies result from changes in assignments of sub-sectoral uses to broad individual sectors ("industrial", "residential", etc.).

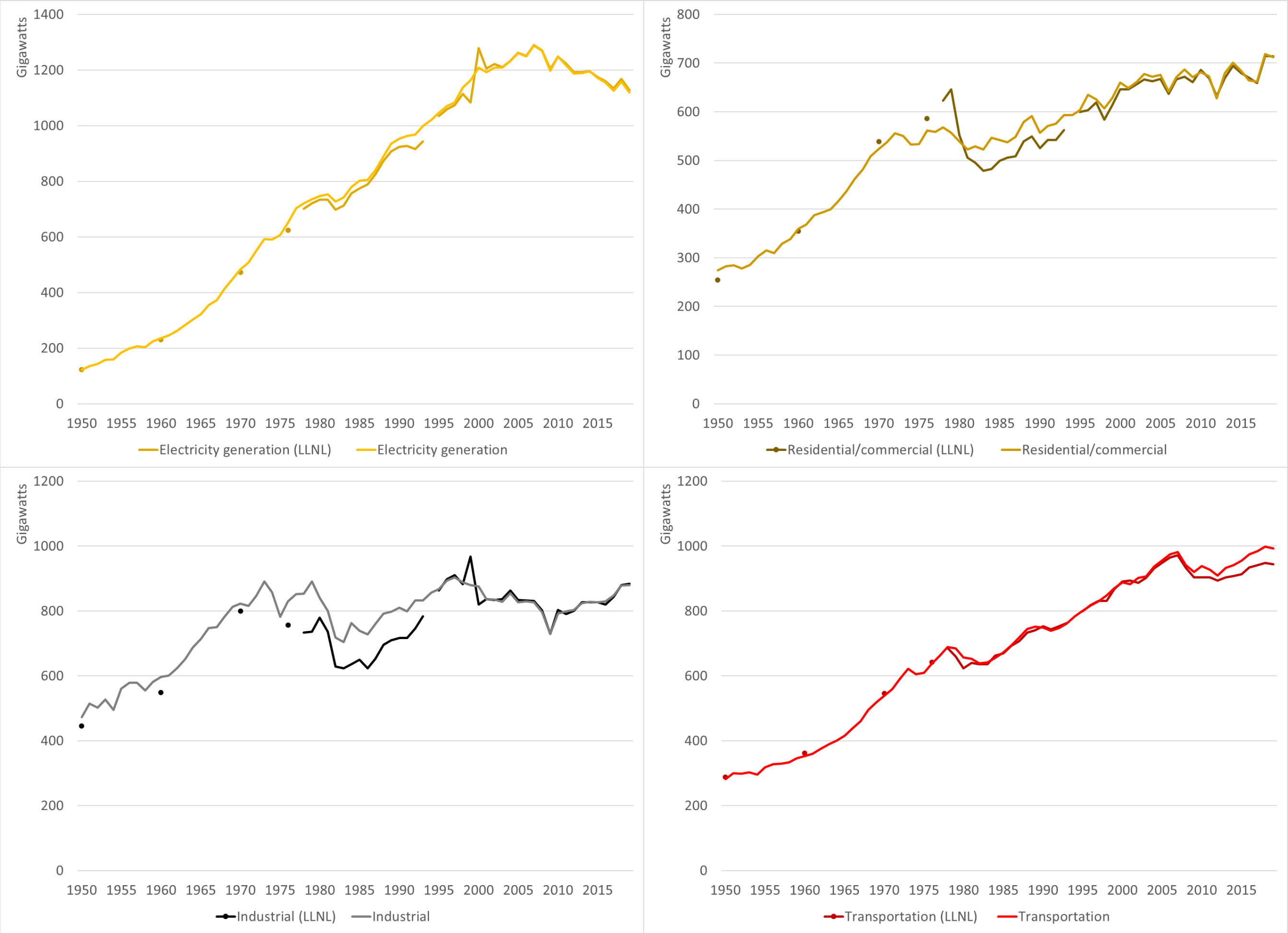

Fig. S27. Comparison of electricity generation and sectoral energy usage from 1950 this work (pale colors) and LLNL (dark colors) (7, 8). For consistency we show our sectoral usage without inclusion of electricity waste heat. For electricity generation, we adjust the LLNL's non-thermal generation by the EIA's applied efficiencies since those of LLNL are not public. Across all sectors, the mean discrepancy is +3%, with a maximum of +17%. By individual sectors, mean differences are residential/commercial 1.9%, industrial 4.6%, transportation 1.1%, and electricity generation 1.3%.

8.3. Error Estimation. Formal error estimation is impossible given the heterogeneity of sources and of methods. We also do not have purely independent estimates to validate against, since many aggregated datasets of U.S. energy use are drawing on the same primary or secondary sources. Especially in the early 1800s, some individual fuel streams may be as much as 50% in error, though all the comparisons made here suggest much smaller discrepancies. We can estimate one component of potential error, that resulting from uncertainty in the energy density of various fuels. Combustion fuels are typically book-kept in government statistics by mass or volume, but may have a range of energy densities depending on their composition: wood can range from 18-22M BTU/cord, coal from 24-28M BTU/ton, and natural gas from 950–1150 BTU per cubic foot. Crude oil energy density is less variable, but is complicated by losses in the refining process. As a rough bound, energy density considerations alone may produce uncertainty of $\sim$10% of the share of total energy comprised by these three fuels in early years when characteristics are less documented, or roughly 9% in 1800 when 90% of the fuel stream was composed of wood or coal.

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