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

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# Energy Transitions in U.S. History, 1800-2019

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**Concerns over climate change have motivated proposals to transform our energy system to reduce $CO_2$ emissions. It is therefore worth examining past energy transitions to understand their causes and constraints. The United States provides a particularly useful case study, since the transition from wood to coal occurred relatively late, while the U.S. government kept detailed records. The U.S. is also anomalous in having extremely high early energy intensity (energy use per GDP), which then improved over time; reasons for the trend have been unclear. We explore both topics by compiling primary sources into a comprehensive dataset of American energy use from 1800 to the present, disaggregated by sector (residential, commercial, agricultural, industrial, and transportation). These data provide several immediate insights. First, the historical trend in U.S. energy intensity reflects not structural features of the economy but specific historical circumstances that led to excessive early energy use for domestic heating. All U.S. non-residential sectors combined did not surpass residential use until the mid-1880s. Second, energy transitions are complex processes composed of numerous changes within individual sectors, often with one sector leading and others following, with infrastructure governing the pace of energy transitions. These data should become an important resource for future research into energy systems, and can inform both academic work and policy studies on future energy transitions. The complete dataset is visualized as an animated Sankey diagram at us.sankey.rdcep.org.**

Energy | Energy Transitions | Energy Intensity | U.S. History

Concern over climate change has led to calls to transform the U.S. energy system to reduce $CO_2$ emissions. Such a transformation is not trivial, since the energy system is both large, with infrastructure valued in the trillions of $USD (1), and fundamental to economic activity. The historical record of past energy transitions may therefore be useful for understanding future possibilities. Since 2003, the Long-term Energy and Growth network, a group of historians, has constructed century-scale timeseries of energy use by fuel type for countries including Britain (2), Italy (3), Sweden (4), Spain (5), Canada (6), the Netherlands, France, and Germany (7). For the U.S., the Energy Information Agency (EIA) released in 2012 an estimate of primary energy use by fuel type since 1775 (8), and a 2014 study provided more extensive sourcing (9).

All these timeseries show a substantial rise in per capita energy use beginning around the Industrial Revolution, accompanied by growth in economic output (Figure 1 and SI Appendix Section 4). Interpreting "energy transitions" in them is less straightforward, because the evolution of human energy use has largely been additive. A transition is commonly defined as a major shift in the composition of the primary energy supply, i.e. as a change in the share of the economy powered by a given source (e.g. (10, 11)). But in most cases, new fuels such as coal, petroleum, and natural gas have been successively added with little or no reduction in previously used energy sources (e.g. (11–14)). The U.S., for example, consumes a similar amount of biofuel now as in the late 19th century (from this work, ∼130 GW as fuelwood and animal feed in 1880 vs. ∼170 GW as fuelwood and ethanol in 2019), but the biomass share of the energy system has dropped from ∼60% to 5%. Very few examples exist of an economy-wide replacement of one energy source by another.

A large body of literature theorizes on how and why energy transitions happen, with little agreement. Much of this work argues that the introduction of new fuels and energy technologies is driven by economic factors, i.e. by rising fuel prices and/or wages (15–17), innovations (9), or labor relations (18). Other studies argue for the importance of non-economic factors. New fuels may have less tangible benefits such as cleanliness (19) or providing a sense of modernity (11), but adoption can be impeded by institutional or regulatory barriers (20). Consumers may be reluctant to change traditional practices (21) and influenced by social pressures (22, 23).

Many authors also emphasize that the speed of transitions is constrained by infrastructure. Introducing a new energy source requires equipment to extract, process, transport, and use the new fuel, and conversely, eliminating an older fuel would require 'stranding' still-useful assets. Infrastructure therefore gives energy systems significant inertia or path dependency, both in past transitions (7, 13, 19, 24) and in potential future ones (25–33). Historical estimates suggest that energy transitions have required at least half a century (10). Understanding these constraints is especially important given the short timelines commonly proposed for decarbonization.

Competing theories of energy transitions have been difficult to resolve in part because we lack detailed histories of energy end use – what consumers were using energy *for* (34, 35). Anecdotal evidence suggests that transitions within individual economic sectors can be complex. Some involve fairly simple substitutions, e.g. fuel oil replacing coal in steamships in the 1910s, but causation is uncertain even in these cases, and the substitutions often depend on prior developments that made a new fuel available. Sectoral transitions can also result from changes in the mix of activities performed. Agriculture, for example, has historically meant mechanical work in fields, but now includes intensive animal husbandry in climate-controlled indoor facilities (e.g. (10, 36)). Finally, structural changes in *how* a primary fuel is used can be important. For example, U.S. households no longer burn coal directly for heating, but the residential sector remains indirectly dependent on coal through coal-fired electricity used for air conditioning and lighting. These changes in end use over historical timescales have not to date been systematically quantified.

R.S. performed analysis, R.S. and E.M. designed experiments, N.M., E.M, and R.S. designed figures, R.S. and E.M. prepared the manuscript.

The authors declare that they have no conflict of interest.

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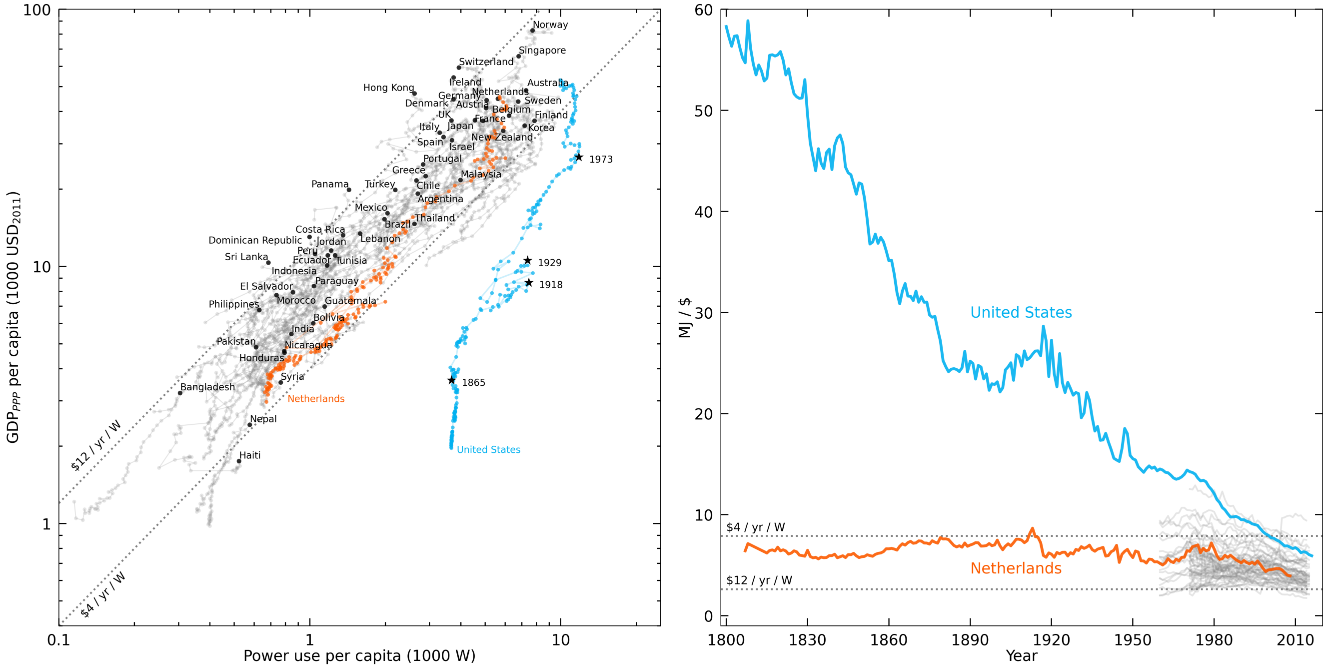
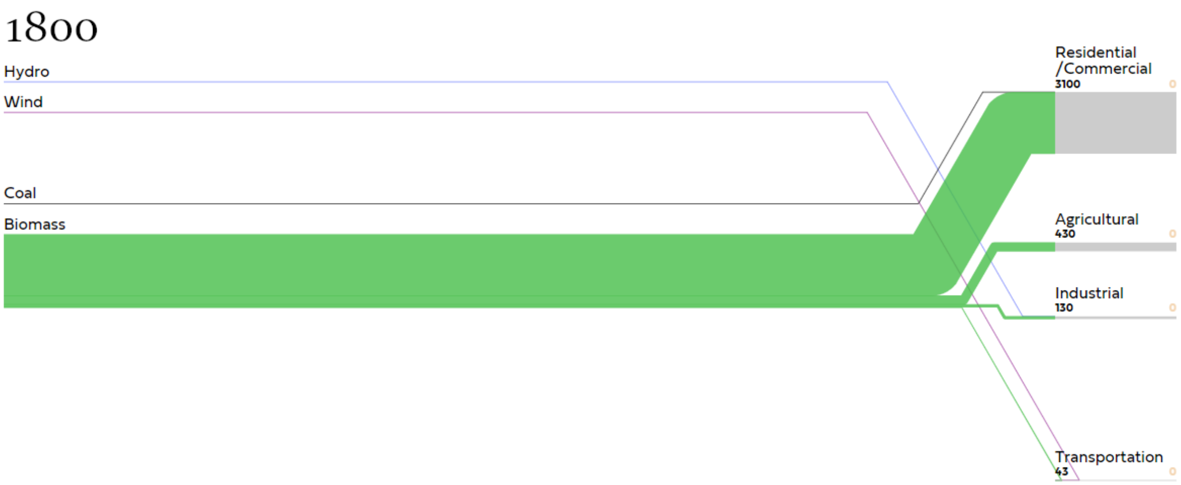


**Fig. 1.** Energy intensity across countries and time, including (gray/black) selected countries from the World Bank from 1971 or after (data coverage differs) (37); (blue) the U.S. from 1800 (this work); and (orange) the Netherlands from 1815 (7). Historical trajectories for each country are shown as linked points. GDP (in 2011 $USD, adjusted to purchasing power parity) is taken from (38) in all cases. *Left:* per capita primary energy use vs. income. Axes are log scale and 1:1 lines are contours of constant energy intensity. Nearly 90% of World Bank country-years shown fall between $4–12/yr/W. The U.S. is an outlier in its high historical energy intensity. Selected dates for the U.S. mark events that affect energy demand: the end of the Civil War (1865), peak coal use (1918), the onset of the Great Depression (1929), and the OPEC oil crisis (1973), which led to high oil and gas prices through the 1970s. The sharp reduction in energy use just above the OPEC marker is driven by the Iranian revolution of 1979. *Right:* energy intensity against time for each country, now in units of MJ/$. Contours from left panel become horizontal lines. *Country selection*: Data shown shown include 46% of country-years in the World Bank database. We exclude countries with 1) population <4M or 2) current or former state-planned economies, or which are 3) major energy producers or 4) in sub-Saharan Africa. (Sub-Saharan African countries are grouped for convenience but include diverse energy histories.) With these included, 67% of country-years would fall between $4–12/yr/W. The Netherlands is shown for illustrative purposes; some other historical timeseries do show early inefficiency, though only Canada is as extreme as the U.S. For figures showing all World Bank countries and multiple historical datasets, and comparison of datasets, see SI Appendix Section 4.

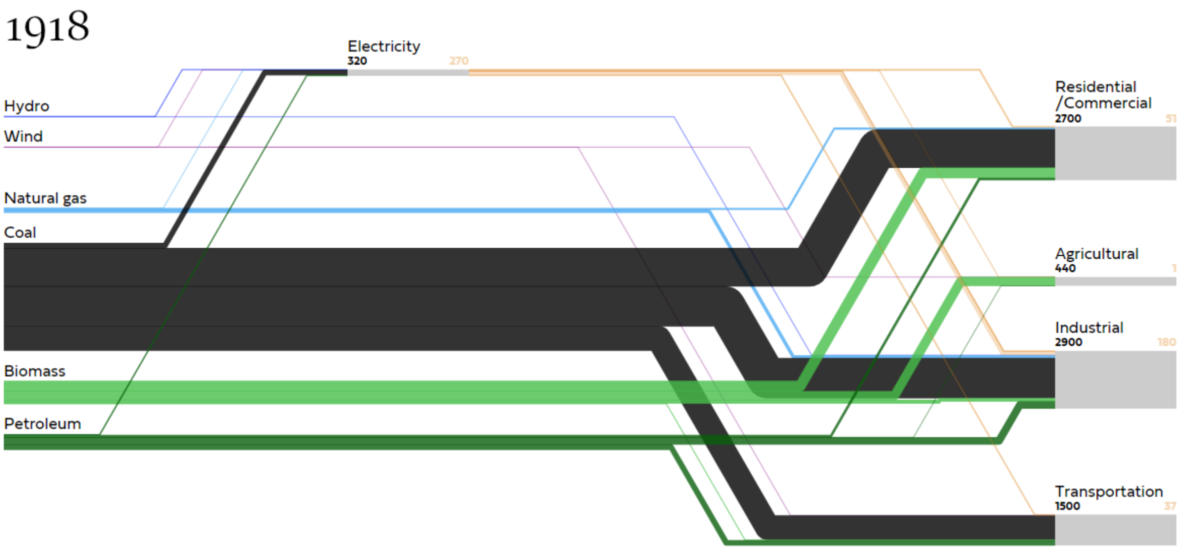
Lack of data on energy end use also hampers understanding of the evolving "energy intensity" of economies (the energy consumed per GDP produced). While many countries show broadly similar relationships between energy use and income (both across time and across countries), the United States is an anomaly, with a prolonged and substantial decrease from initial high values (Figure 1). In 1800, U.S. energy intensity was more than 50 MJ/$, >5 times above that of most contemporary countries. Over the next two centuries, it dropped by an order of magnitude: U.S. per capita income grew by ×27 while per capita energy use grew only by ×3. This long-term U.S. trend has not been explained. Authors have attributed it to any or all of improvements in engine efficiencies (10), "fuel quality" (9), or end use efficiency (9, 39), but do not explain why these factors would not equally affect other countries. Explanations for a more recent downturn experienced by many countries since the 1980s are also diverse, and include innovations in technology or human capital (4, 39–46); rising fuel prices (47); offshoring of energy-intensive industries (48); and changes in the sectoral composition of the economy (49, 50). Understanding the factors governing energy intensity is especially important for climate change concerns, since many policy analysis models assume that current trends will continue indefinitely, (51, 52), reducing the effort needed for climate mitigation.

This work seeks to address these questions by compiling a comprehensive history of energy use in the U.S. disaggregated by sector. A focus on the U.S. is particularly appropriate not only because of the country's atypical energy intensity evolution, but because the U.S. underwent the critical transition from wood to coal relatively late compared to contemporaries like the United Kingdom (2), at a time when government agencies and private sources kept abundant records (53). U.S. energy use is extensively documented in primary sources including the U.S. census, government agency reports, industry surveys, and company manuals and accounts, allowing us to construct sectoral estimates at roughly 10-year intervals from 1800—1949 (which we scale to yearly production), and annually thereafter. We report in per capita units throughout to disentangle structural changes in the economy from population growth. (U.S. population grew by more than ×60 from 1800–2019.)

In the remainder of this paper, we provide an overview of the dataset and show selected results. The SI Appendix contains extensive discussion of sources, methodology, core assumptions, physical conversion factors, validation exercises, and additional results. The final dataset is publicly available and can be viewed online as an animated Sankey diagram (http://us.sankey.rdcep.org/). Figure 2 shows selected panels of the Sankey animation as illustrations.


1800
Hydro
Wind
Coal
Biomass
Residential
/Commercial
3100
0
Agricultural
430
0
Industrial
130
0
Transportation
43
0


1865
Hydro
Wind
Coal
Biomass
Petroleum
Residential
/Commercial
2800
0
Agricultural
370
0
Industrial
320
0
Transportation
170
0


1918
Electricity
320
270
Hydro
Wind
Natural gas
Coal
Biomass
Petroleum
Residential
/Commercial
2700
51
Agricultural
440
1
Industrial
2900
180
Transportation
1500
37

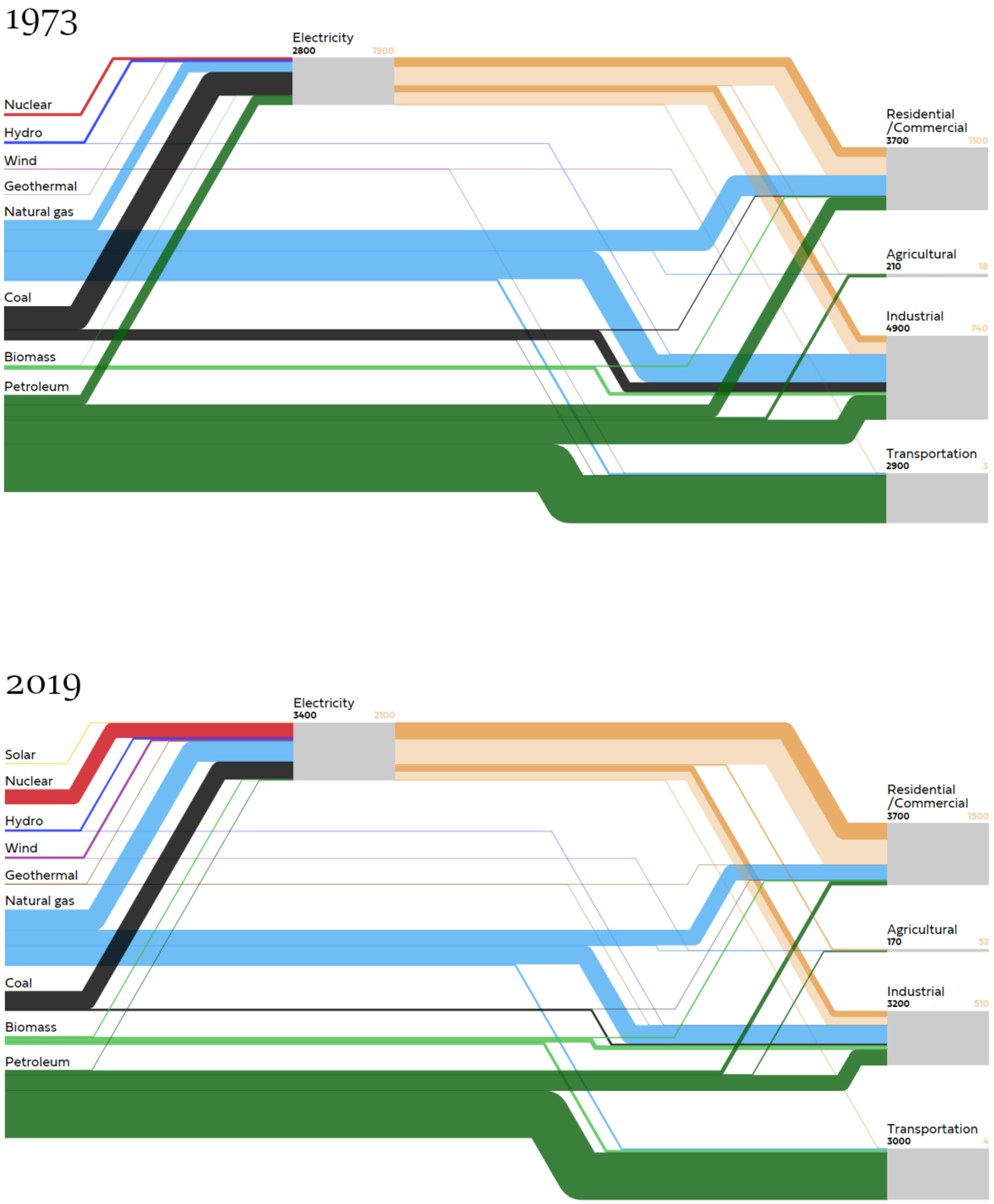


**Fig. 2.** Illustrative frames from the Sankey animation of the evolving U.S. energy system (http://us.sankey.rdcep.org/). Thickness of lines and boxes denote the magnitude of per capita energy flows from primary energy sources (*left*) to end uses (*right*), with electricity generation shown as an intermediate transformation. Color code follows convention of Lawrence Livermore (LLNL) Sankeys (54), but unlike LLNL we explicitly allocate waste heat from electricity generation so that left and right totals are equal. We treat efficiency of non-thermal electricity generation (hydro, solar, and wind) as 1; note that thermal sources require $\sim 3\times$ as much primary energy per electricity output. Years shown and their respective total per capita energy use are: 1800, the beginning of our timeseries shown in Figure 1 (3,700 W/cap.); 1865, the end of the Civil War, after which railroads and coal usage accelerated (3,700 W/cap.); 1918, the peak of coal dominance (7,500 W/cap.); 1973, the year of the OPEC oil crisis and the peak per capita energy use in U.S. history (12,000 W/cap.); and 2019, the end of our timeseries (10,000 W/cap.). Energy use is rounded to 2 significant figures.

## Results

Our sectoral dataset shows that the U.S. underwent enormous structural changes during two centuries of growth. The economy evolved from almost purely agrarian, with little energy use outside of homes and farms; to one dominated by industry and powered primarily by coal; to a more diverse energy economy with a weaker role for industry and a substantial portion of the primary energy supply converted to electricity (Figure 2). Early U.S. energy use is overwhelmingly dominated by wood-fueled home heating. In 1800, industry and transportation combined made up less than 5% of U.S. energy use, and not until the mid-1880s did all sectors combined outweigh residential use. Coal use rose rapidly after the Civil War, enabled by an expanding railroad network and fueling the growth of industry and transportation. Per capita energy use in industry and transportation grew by ×12 and ×11 from 1860–1920, while that in households and farms actually declined (Figure 3, which shows historical U.S. energy use by fuel and sector). The successive addition of new fuels (petroleum, natural gas, and nuclear) then diversified U.S. energy sources, with petroleum powering a growing transportation sector.

These data make clear that the United States' high early energy intensity was driven by astonishingly high residential energy use. In 1815, U.S. homes burnt ∼2800 W/cap. of fuelwood, five times the *total* energy usage in the wealthier Netherlands at the time (565 W/cap. in Figure 1). Problems with U.S. household heating are extensively documented in contemporary letters and accounts, which describe inefficient open fireplaces, frigid houses, and vast consumption of wood (21, 55). These results have major implications for interpreting energy intensity. Historically, the residential sector has not been counted in GDP – the sum total of monetary transactions – since household labor was and is almost entirely unremunerated. Firewood in the U.S. was also abundant and cheap or, in rural areas, free. Early U.S. energy use therefore involved almost no categories counted in the economy.

The lesson of the U.S. example is that energy is not a single category. The steady drop in U.S. energy intensity through the 19th century (Figure 1b) resulted not because some metric of "efficiency" improved but because the income-generating industry and transportation sectors made up increasing shares of U.S. energy usage. Per capita residential energy use declined only late in the century, when U.S. households outside the urbanized Northeast finally adopted both coal and heat-retaining stoves (21). It may therefore be more useful to redefine energy intensity as GDP per *non-residential* energy use. With residential energy removed (SI Appendix Section 4), U.S. energy intensity remains far more constant over time, and exhibits a more typical "inverted U" evolution (5): values are steady until about 1865, rise by ×2 during the build-up of the industrial sector to a peak just after 1910, and then decline steadily to about half the 1800 value. (Note that several prior studies also effectively omit all residential heating (39) or that part of it from non-marketed fuels (56).)

Sectoral disaggregation also allows us to analyze energy transitions in detail, providing important insights into plausible pathways for any future transition aimed at decarbonization. The evolution of coal usage is especially useful in this regard because of its complexity: coal rose to dominance, began a long decline, was revived by a newfound use, and now appears again headed for extirpation (Figure 4).

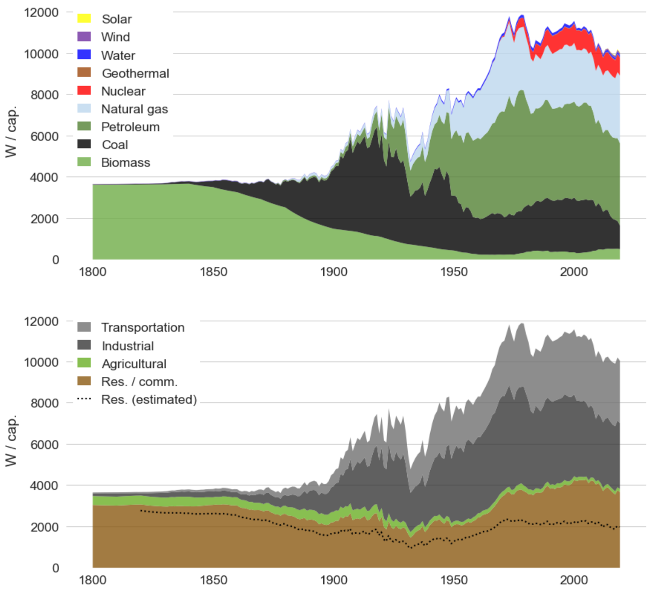


**Fig. 3.** Evolution of U.S. per capita energy use, by fuel (*top*) and by sector (*bottom*). For analogous figures in absolute units, and by fuel for individual sectors, see SI Appendix Figures S1–S11 We estimate a split between residential and commercial sectors (dotted line) using labor statistics between 1820–1949; see SI Appendix Section 3.1.1.Both panels show the evolution of the U.S. from a biomass-powered agrarian economy to a mixed industrial economy, accompanied by a tripling of per capita primary energy use to its peak in 1973, just before the OPEC crisis. Industry and transportation grew ∼50 to 100-fold: industry from 130 to 4900 W/cap. in 1973 before falling to 3200 W/cap. and transportation from 43 to 3000 W/cap. Commercial use grew more slowly, from ∼300 to 1700 W/cap, and on-field agricultural energy use actually declined as horses were replaced by motorized equipment, from 430 to 170 W/cap. (It remains lower even accounting for endogenous energy in fertilizer; see SI Appendix Section 3.2). Residential use declined with the introduction of more efficient stoves (from ∼2800 W/cap. in 1800 to 900 W/cap. in the 1930s) before rebounding to roughly 2000 W/cap. today. The decline in overall energy use after 1973 was driven by a combination of improved end-use efficiency, deindustrialization, and, in the last two decades, replacement of coal-powered steam turbines with more efficient gas-fired combined-cycle plants for electricity generation.

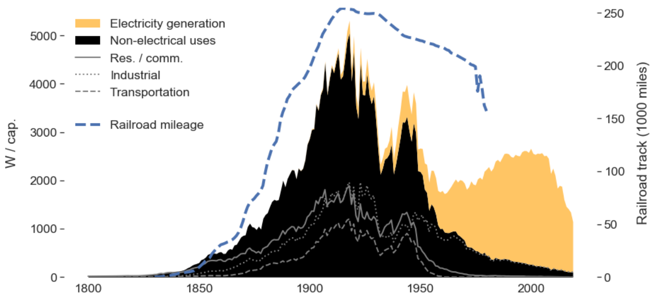


**Fig. 4.** The rise and fall of coal, 1800–2019. Figure shows per capita coal use in non-electrical (black) and electrical (yellow) sectors as a stacked area chart. Grey lines show coal use in individual sectors. Per capita coal use rose to a peak in 1918. Early coal usage was dominated by the residential sector (solid gray) but enabled by the railroads that carried coal (track miles in blue dashed line, from (57)). By 1910, industry had become the largest coal user (dashed gray). After 1918, coal use declined in both per capita and absolute terms, driven by rising prices, uncertain supply, and stalled growth in railroads. WWII provided a temporary boom, but longer-term, coal avoided extirpation in the U.S. economy only because it found a new use in the growing electricity sector (yellow). From the 1950s to the present, the only non-electrical use of coal has been a shrinking role in industry (gray dotted). Since 2005, coal is being replaced in electricity by cheap fracked natural gas, and usage has dropped by over half even in absolute terms.

The transition from wood to coal transformed American life in every sector, allowing a radical expansion of the U.S. energy supply. That transition did not begin until decades after Pennsylvania coal was first burnt in households and industry in the early 1800s, since coal could only be widely used if some means existed to move it from mines to rural consumers. While canals played an early role, the expansion of railroads after the Civil War appears the critical factor (Figure 4, see (19, 21, 58)). By 1918, coal had risen from a minor fuel to underpinning the whole U.S. economy, accounting for 71% of primary energy use and dominating in every sector (Figure 2). At this point coal provided ∼5× the absolute energy as had wood at its peak, and fuelwood use was declining in absolute as well as per capita terms. The peak in coal use was however short-lived. The 1910s–20s saw a succession of crises – violent labor unrest in coal mines and railroads, including the coal strike of 1914 (59–62); coal shortages and spiking prices exacerbated by WWI (59, 60, 63); and stalled demand in the overbuilt railroad industry (64) – followed by a decline in per capita and even absolute coal use (Figure 4 and SI Appendix Figure S1). Coal was eradicated from one sector after another, until from the 1960s on its only use outside the electric sector has been in industry, a role that has gradually shrunk along with U.S. manufacturing and especially steelmaking (63).

Coal in the midcentury U.S. might then seem a textbook case of an energy transition involving complete fuel extirpation – except that extirpation did not actually happen. While absolute use of coal dropped for four decades from the 1910s, other than a bump during WWII (SI Appendix Figure S1), it remained the dominant fuel in the tiny electric sector (Figure 5), and when electricity boomed in the U.S. in the 1960s, coal followed. Coal use peaked in absolute terms in 2005, with over 90% of its use for electricity generation. The advent of cheaper fracked gas then sent coal into decline again, and in just over a decade since, its use has fallen by half.

This history shows both the difficulty of eradicating an existing fuel from an economy, and the practical difficulty of introducing a new one. These issues are best understood by examining transitions within individual sectors. In Figure 5, we show the evolving fractional share of primary energy sources in four sectors and the fractional contribution of energy sources to electricity generation. Because there is no standard definition of an energy transition, we arbitrarily define one as beginning when a previously dominant energy source falls below 70% of its peak share, and ending when it drops below 30% of its peak share. By this definition, each U.S. sector has experienced at least one transition since 1800 (gray shading in Figure 5), and transitions in agriculture and electricity are currently ongoing. Of the 7 sectoral transitions that are complete, the mean length is 18 years.

The sectoral histories of Figure 5 show the effects of infrastructure constraints on energy history. New fuels often penetrate slowly into the first sector adopting them, but transitions can be rapid once energy infrastructure is already developed. Coal's journey through the large residential / commercial sector is strongly asymmetric for this reason. Coal adoption involves a nearly century-long ramp-up, with the final identified transition (the 21-year period 1883–1904) coming after transitions in the much smaller industrial and transportation sectors were complete and the coal-powered railroad network had been built out. Forty years later, the transition of home heating away from coal (initially to oil and then to natural gas) came very late, starting a quarter-century after transitions in industry and transport, and occurred astonishingly quickly, in just 4 years by our definition.

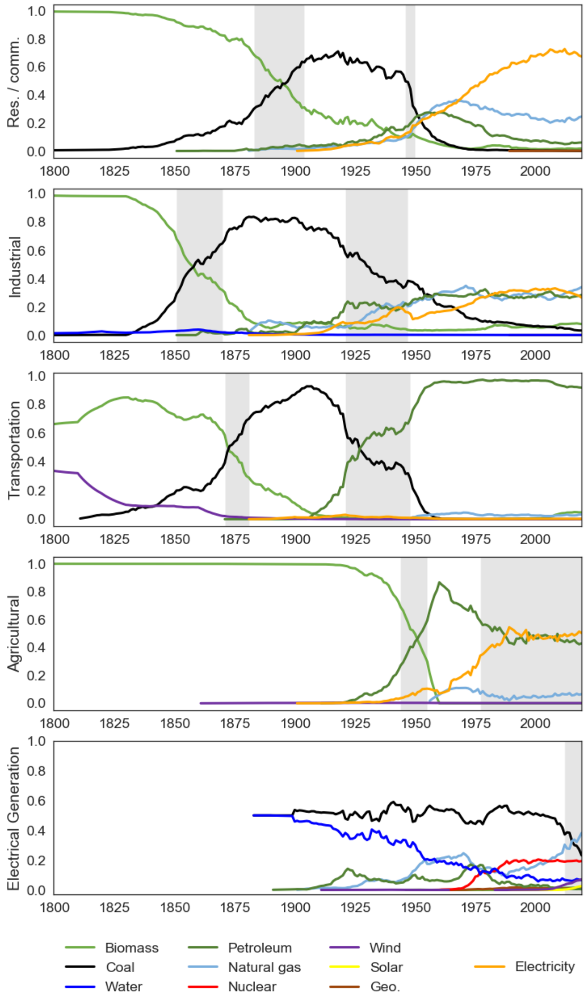


**Fig. 5.** Fractional share of primary energy sources in each sector, 1800–2019. Top four panels show the four economic sectors. Fuels are color-coded as in Figure 2, and represent direct use. "Electricity" (yellow) is the primary energy required to produce electricity used in the sector, i.e. it includes the waste heat of thermal generation. Bottom panel shows the fractional contribution of each primary source to electricity production, i.e. the share of electricity produced, not of primary energy in. (See SI Appendix Section 3.5.1.) Gray shading highlights energy transitions defined as periods when a previously dominant fuel falls from 70–30% of its peak share. These are: residential/commercial 1883–1904 and 1946–1950; agriculture 1944–1955 and 1977–present; industry 1851–1870 and 1921–1947; transportation 1871–1881 and 1921–1948; and electricity generation 2012–present. Electricity is clearly in transition at present but agriculture has stabilized; our transition definition becomes problematic when multiple fuels contribute equally to a sector. Note that when industrial and transportation sectors made their wood-to-coal transition they were less than 1/10th the size of residential / commercial. In transportation, the coal-to-oil transition is distorted because it involves addition of an entirely new usage category. Locomotives initiated some use of fuel oil for external-combustion steam in the 1910s, but transitioned fully to petroleum only in the 1950s, after development of heavy-duty diesel-electric drives. The sectoral transition appears longer because of the intervening rise of the gasoline-powered automobile. Were they considered separately, the transition in automobiles would be complete by ∼1905, when gasoline outcompeted electricity (65), and that in trains would not begin until ∼1950. This example is a rare case where end-use technological development was the limiting factor in a transition.

The rule that late transitions can be rapid appears reasonably general. Two of the fastest transitions, the substitution of petroleum for coal in residential heating (4 years from 1946–1950) and for biomass in agriculture (11 years from 1944–1955), both followed a long development of oil infrastructure and complete transitions in industry and transportation. By the time the residential/commercial and agriculture sectors began converting to petroleum, extensive oil extraction and distribution networks – wells, refineries, and pipelines – were already in place. (Residential heating then shifted quickly to natural gas as the gas pipeline network was built out.) The second-fastest sectoral transition in U.S. history, the conversion of steam locomotives in transportation from wood to coal (10 years from 1871–1881), began only after coal had become dominant in the similar-sized industrial sector. These examples highlight the fact that preexisting energy infrastructure developed for one sector shortens and eases transitions in others.

## Discussion

The dataset compiled here of the sectoral evolution of the U.S. energy system allows new insight into the dynamics of energy transitions. The growth in U.S. energy use and the successive addition of new energy sources have long been documented. We can now add an understanding of the real and substantial changes over time in how energy sources have been employed. Tracking energy end use allows us to identify timescales of transitions in individual sectors and to distinguish between fuel substitutions and changes in sectoral activities. We can see that broad economy-wide energy transitions are in fact complex processes composed of numerous changes within individual sectors, often with one sector leading and others following.

One key general lesson is that energy supply infrastructure plays a substantial role in governing the pace of energy transitions. Coal, petroleum, and natural gas were all used for decades at a small scale, especially near the mines and wells of energy-rich Pennsylvania, before railroads and pipelines allowed them to make a national impact. Electricity use similarly boomed only with substantial investment in the grid. Conversely, once supply infrastructure exists, sectoral transitions have been very rapid. Midstream infrastructure appears to be the primary limitation affecting past transitions, though end-use technology is the constraint in a few cases, especially in transportation. Lack of high-powered diesel engines retarded the transition of railroads from coal to oil, and arguably battery technology is currently inhibiting a transition of motor vehicles from gasoline to electricity.

A second lesson provided by the historical perspective is that recent events affecting the energy economy are not particularly unusual. Recent energy crises and energy transitions all have historical analogues. The oil and gas crisis of the 1970s, for example, resembles the coal crisis of the 1910s. Both involved price spikes and fuel shortages, and both turned a period of rapid growth in use of a fuel into a long-term decline (59–63). Both also both led to a long-term reduction in the energy/GDP ratio (clearly visible in Figure 1). By contrast, crises that are financial in origin – the Great Depression of the 1930s and the Great Recession of 2008–2010 – produced sharp but temporary reductions in energy usage but left no lasting structural changes in the energy system.

Similarly, the U.S. is currently in the midst of an energy transition in the electric sector that is analogous in dynamics to past transitions. The advent of cheap natural gas from fracking has slashed coal use by half in just over a decade. By our definition, the transition began in 2012 and given current trends would complete around 2021, a total of 9 years, similar to past transitions in transportation (biomass to coal, 10 years) and agriculture (biomass to petroleum, 11 years) and slower than that in residential heating. The rate of decline in per capita coal usage is also similar to past rates (Figure 4), and the current transition could in fact be seen as the last stage in the progressive elimination of coal from the U.S. energy economy. As with past transitions, the change has led to shutdowns and job losses in the energy industries affected, but its broader economic effects are barely noticeable.

We have described only the broadest results from the historical dataset, and many further avenues of research are possible. Given the importance of infrastructure in energy transitions, one clear research need is on the relative role of public and private investment in energy assets. The federal government has long played a heavy role in U.S. energy development, subsidizing or directly building railroads (1860s), hydroelectric dams (1930s), pipelines (1940s), the interstate highway system (1950s), and the electrical grid (1940s-1960s). It has also promoted new energy technologies through research funding (nuclear), subsidies (wind, solar) and mandates (ethanol). However, the relationship between government and private actors in driving energy transitions remains an open question.

A second research need is on the role of existing infrastructure in delaying or disincentivizing transitions. While some historical transitions have involved complete replacement of end-use technologies (e.g. locomotives, residential heating), in other cases archaic technologies persisted even after a cheaper or better energy source was available. Existing waterwheels, for example, remained in use well into the twentieth century, but in an era of growth were soon outnumbered by coal-fired steam engines. Any future transitions will likely occur in conditions of relatively flat per capita energy use, and so will involve substitutions rather than additions.

Understanding the history of our energy system can help us evaluate its potential future. Proposals to decarbonize the energy system generally involve a transition of the electric sector to carbon-free generation, followed by electrification of downstream sectors (possibly other than industry). The historical record suggests both optimism and caution. Sectoral transitions can be rapid, and electrification continues existing trends. (In 2019, a third of U.S. primary energy inputs were converted to electricity, compared with 2% in the 1910s.) History suggests however that any needed expansion of midstream infrastructure – the electrical grid – can present a significant obstacle. It is also important to note that by our definition, the U.S. has not yet begun a transition away from fossil fuels. In 2019, non-fossil energy sources still comprise less than 20% of the total U.S. energy system. (This statement remains true even if hydropower, wind, and solar electricity are computed with assigned thermal efficiencies.) In the electric sector, the non-fossil share of generation has been growing, but slowly, from 29% in 1989 to 38% today, and upcoming decades will see the shutdown of America's aging nuclear plants, themselves the legacy of a failed energy transition. It is helpful to realize, however, that proposed future transitions are no more radical than the transformations experienced in the past. Over two hundred years of U.S. energy history, change has been the norm.

## Methods

We summarize briefly here; the SI Appendix contains more a extensive discussion of sources, methodology, core assumptions, physical conversion factors, validation exercises, and additional results.

*Sectors.* In this work we disaggregate U.S. energy end use into four major sectors, and make a preliminary attempt at estimating the energy consumption of a fifth: 1) *residential/commercial* are often aggregated as "retail deliveries" for various fuels in contemporary sources; 2) *agricultural* counts all on-field use, but not endogenous energy in fertilizer or pesticide inputs; 3) *industrial* includes all manufacturing and on-site extraction, and 4) *transportation* includes all movement of people and freight between locations, but not on-site at individual facilities. See SI Appendix Sections 3 and 6 for details. For residential and commercial disaggregation we use EIA estimates after 1949; we extend the breakdown before 1949 by scaling by the difference of population and total employment as reported in the Census, to infer household workers.

*Sources.* Wherever possible, we base estimates on primary sources: information produced by someone contemporary to the historical period in question. The chief primary source for the pre-1949 period is 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), although several energy sources (e.g. early wind) are not tracked by the agency. 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. Wherever possible, we also cross-check values using multiple sources.

In total the dataset draws on approximately 100 different documents, not distinguishing a dozen distinct Census Bureau reports that are assigned a single citation (66). Besides the Census, six other key sources or sets of sources are the EIA (67); the Department of Agriculture's Agricultural Census (68); the annual statistical aggregation known as the Statistical Abstract of the United States (69); a prior collection of estimates of U.S. energy use (70); the Cambridge Historical Statistics of the United States (57); and, for validation purposes only, the Lawrence Livermore National Laboratory's (LLNL) estimates of energy flows (54). See SI Appendix Section 7, which details our estimates for each time period in detail. For the earliest years, many estimates are derived by scaling historical data by some proxy – for example, the power of mechanical waterwheels is estimated from the production of cotton – using a scaling factor developed from later records. All physical assumptions and details of estimates for each fuel stream are described in SI Appendix, Sections 6 and 7.

*Electricity generation.* Some of our choices are not standard practice in energy Sankey diagrams and differ from (54). First, 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. Second, while many estimates assign renewable generation the same efficiency as thermal generation, this practice makes no sense for historical studies since the contribution of renewables would then vary arbitrarily with the evolution of engines and turbines. In this work we assign a thermal efficiency (from EIA estimates) to nuclear and geothermal electricity produced in steam turbines, but we 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. When computing fuel shares for the electrical sector in Figure 5, we book-keep their shares of electricity produced rather than of primary energy in. See SI Appendix Sections 6.2.2 and 3.5.1.

*Validation.* We validate our results by checking them against two previous independent estimates of historical U.S. energy use. Validation is discussed in detail in SI Appendix Section 8; we summarize here. For the period 1800–1949, we compare to a timeseries of primary energy use by fuel from 1775 released by the EIA in 2012, henceforth EIA2012 (8). This timeseries is poorly documented, but is analogous to ours for most fuel streams. In some cases, our estimates are more complete: for example, the EIA2012 estimate for biofuel omits grass, hay and grain for animal feed; windpower omits mechanical pumps, sailships, and turbines not connected to the grid; and hydropower omits non-marketed electricity and mechanical work from gristmills and waterwheels. Using only comparable fuel streams, mean discrepancy between our data and EIA2012 across all years and fuels (including fuelwood) is -2% and maximum -12%.

For the period 1950-2019, our estimates are largely based on EIA tables, but we can validate energy use by both fuel and sector against the Energy Flow Charts of the Lawrence Livermore National Laboratory (henceforth LLNL), available in a variety of agency reports for 1950, 1960, 1970, 1976, and 1978 (71) and annually thereafter for all years except 1993 (54). 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.

The full dataset is available upon request to the authors, and is visualized at us.sankey.rdcep.org.

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