ACEEE American Council for an Energy-Efficient Economy

POLICY BRIEF

The United States Can Electrify Most Fossil Fuel Use: Here Is What Needs to Happen to Make This Possible

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KEY FINDINGS

- The United States can electrify about 90% of its current energy use. Doing so will reduce carbon emissions and often consumer costs while improving public health.
- There has been much recent progress on electrification, including growing sales of electric vehicles and a variety of efforts to promote heat pumps. These successes provide momentum that we can build upon.
- For vehicles, federal tax incentives and emissions standards, state zero-emissions vehicle requirements, and utility and private-sector build-out of charging infrastructure will all help to grow the EV market. These policies, as well as continued technology and production improvements, can steadily lower EV costs so that ultimately EVs are less expensive to purchase and operate than conventional vehicles.
- For buildings, heat pumps are generally the lowest-cost strategy for new buildings; building codes should require or strongly encourage heat pumps. For existing homes and apartments, building shell upgrades are an important complement to electrification, reducing costs and improving comfort. Utility and government incentives and technical assistance, manufacturer R&D to improve systems and reduce costs, and long-term policies such as state "clean heat standards" and state and local building performance standards can gradually spur electrification.
- For industry, the majority of process heating can be electrified with industrial heat pumps, electric boilers, and other electro-technologies. Companies should pursue strategic energy management to reduce energy demand. Some companies will pursue these strategies as part of their sustainability goals, but ultimately some combination of customer demand for low-carbon products and future carbon pricing will likely be needed.
- The power sector can decarbonize through increased utility investment in carbon-free electricity generation (e.g., renewable and nuclear power) as well as some power generated with "green" hydrogen (produced with clean electricity) and some with natural gas coupled with carbon capture and either utilization or storage. To serve growing electric loads, utilities will need to expand generation, transmission, and distribution as well as energy efficiency and load management programs that reduce peak loads. Utilities and regulators should plan for this expansion.
- Approximately 10% of fuel use will remain difficult to electrify; this brief also discusses how to decarbonize those uses.

Introduction

Electrification is a critical strategy for reducing carbon emissions.[1] In most applications, technologies such as high-efficiency heat pumps and electric vehicles reduce energy use and carbon emissions and can reduce expenditures, benefiting consumers and the economy. Because efficient electrification reduces energy use, we see it as a key energy efficiency strategy, complementing other more traditional forms of energy efficiency such as building shell improvements. Building shell improvements to reduce load and improve comfort and health[2] are critical complements to electrification, helping to reduce the direct and indirect costs of electrification (e.g., the costs of heat pumps but also the costs of electric infrastructure to power these heat pumps).[3]

In 2019, ACEEE expressed general support for efficient beneficial electrification as a form of energy efficiency, where "beneficial" means saving energy (in total Btus), saving money, and reducing emissions.[4] Since then, ACEEE and many others have conducted studies showing that high-efficiency electrification strategies such as heat pumps[5] and electric vehicles[6] either meet these criteria or are on a path to meeting these criteria. Thus, many applications now meet our efficient beneficial electrification criteria. Last year we estimated that about 90% of U.S. energy use can be electrified, helping to dramatically decarbonize U.S. energy use as electric generation also decarbonizes.[7] In this brief, we build on these recent findings in order to spell out steps that are being taken to get there, what more is needed, and how to decarbonize the remaining 10% of fossil fuel use. Applications and markets are complex and thus the path to efficient electrification is also complex; this brief analyzes some of these complexities to identify the steps we must take to largely decarbonize our economy.

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[1] IEA. 2022. *Electrification*. www.iea.org/reports/electrification.

[2] ACEEE. 2015. *Energy Efficiency and Health*. www.aceee.org/fact-sheet/ee-and-health.

[3] Nadel. 2023. "Coming Electrification Will Require the Grid to Evolve." www.aceee.org/blog-post/2023/02/coming-electrification-will-require-grid-evolve.

[4] Molina. 2019. "Electrification and Efficiency: Crafting an Enduring Relationship." www.aceee.org/blog/2019/01/electrification-and-efficiency.

[5] Nadel and Fadali. 2022. *Analysis of Electric and Gas Decarbonization Options for Homes and Apartments*. www.aceee.org/research-report/b2205.

[6] Slowik et al. 2022. *Assessment of Light-Duty Electric Vehicle Costs and Consumer Benefits in the United States in the 2022–2035 Time Frame*. https://theicct.org/publication/ev-cost-benefits-2035-oct22/.

[7] Nadel. 2022. "What Is the Role of Fuels in a Decarbonized Future? What Is the Potential Role for Gas Utilities?" https://aceee2022.conferencespot.org/event-data/pdf/catalyst_activity_32514/catalyst_activity_paper_20220810190553091_0258fe61_1bbe_435b_a328_97d81e25aa73.

Transportation

The transportation sector is the largest source of U.S. carbon emissions, yet only a small fraction of its energy needs are currently met by electricity, despite electric vehicles being approximately four times more efficient than gasoline vehicles.[8] Electric vehicles also have substantial health benefits. Analysis by the American Lung Association estimates that if all passenger vehicles were EVs, due to reduced emissions, by 2050 there would be 89,300 fewer premature deaths.[9] For zero emissions trucks, they estimate 66,800 fewer premature deaths.[10]

Electric vehicles (EVs) are now available in most vehicle classes ranging from cars to 18 wheelers.[11] The Biden administration's goal is for 50% of new light-duty vehicle sales to be electric by 2030.[12] Battery electric vehicles (BEVs; vehicles powered by batteries and without an engine) generally cost more up-front but then have lower operating costs. In the medium-term, they might not cost more than conventional vehicles. For example, the International Council for Clean Transportation estimates that for light-duty battery electric vehicles (BEVs) "price parity with conventional vehicles will occur between 2024 and 2026 for 150- to 200-mile range BEVs, between 2027 and 2029 for 250- to 300-mile range BEVs, and between 2029 and 2033 for 350- to 400-mile range BEVs."[13] Likewise, they find that "by 2030, the total cost of ownership of battery electric long-haul trucks will likely be lower than that of their diesel counterparts in all representative states considered."[14]

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[8] Westbrook. 2022. "Electric Vehicles Are Way, Way More Energy-Efficient than Internal Combustion Vehicles." www.motortrend.com/news/evs-more-efficient-than-internal-combustion-engines/.

[9] American Lung Association. 2023. *Driving to Clean Air: Health Benefits of Zero-Emission Cars and Electricity*. www.lung.org/getmedia/9e9947ea-d4a6-476c-9c78-cccf7d49ffe2/ala-driving-to-clean-air-report.pdf.

[10] American Lung Association. 2022. Driving to Clean Air: Health Benefits of Zero-Emission Trucks and Electricity. www.lung.org/getmedia/e1ff935b-a935-4f49-91e5-151f1e643124/zero-emission-truck-report.

[11] Lu. 2022. "All Electric Semi Truck Models in One Graphic." www.visualcapitalist.com/every-electric-semi-truck-model-in-one-graphic/.

[12] The White House. "FACT SHEET: Biden-Harris Administration Announces New Private and Public Sector Investments for Affordable Electric Vehicles." www.whitehouse.gov/briefing-room/statements-releases/2023/04/17/fact-sheet-biden-harris-administration-announces-new-private-and-public-sector-investments-for-affordable-electric-vehicles/.

[13] Slowik et al. 2022. *Assessment of Light-Duty Electric Vehicle Costs and Consumer Benefits in the United States in the 2022–2035 Time Frame*. https://theicct.org/publication/ev-cost-benefits-2035-oct22/.

[14] Basma et al. 2023. *Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-Haul Trucks in the United States*. https://theicct.org/publication/tco-alt-powertrain-long-haul-trucks-us-apr23/.

Many vehicle manufacturers are pledging to introduce new EV models and ultimately to primarily sell EVs.[15] The 2021 federal Bipartisan Infrastructure Law (BIL) and the 2022 Inflation Reduction Act (IRA) include tax incentives for electric car and truck purchases and large investments in charging infrastructure. The U.S. Environmental Protection Agency (EPA) has also proposed greenhouse gas emissions standards that could result in more than 60% of light-vehicle and 40% of medium- and heavy-vehicle sales being electric by the early 2030s.[16] These draft rules should be strengthened to better support efficiency opportunities for EVs and conventional vehicles and then finalized.[17] At least 18 states have adopted requirements for light- and/or heavy-duty market sectors specifying that growing proportions of vehicle sales be zero emission;[18] other states should consider these standards, steadily increasing the requirements until most vehicles are electric.

Many electric utilities are investing in charging infrastructure and reinforcing their distribution systems. The cost of these improvements is much greater than the federal funding; substantial utility investment will be needed. Given the speed with which these large transportation loads can materialize under ambitious policies, and the timelines to build major utility infrastructure (e.g., two to four years or more to design and build a substation[19]), utilities should proactively plan and start buildout of the grid today so that capacity is in place in time for the large ramp up in EV adoption.

Infrastructure for truck fleets will be particularly important since, unlike passenger vehicles, these tend to be concentrated in particular locations.[20] A recent study by Synapse Resource Economics found that utility investments in truck infrastructure can ultimately benefit all electric ratepayers as the income from electricity sales for trucks more than offsets the cost

[15] Rubio-Licht and Roach. 2022. "Here Are the Main Electric Vehicle Goals Set by Automakers and Major Markets." www.protocol.com/climate/electric-vehicle-automaker-goals.

[16] EPA. 2023. "Biden–Harris Administration Proposes Strongest-Ever Pollution Standards for Cars and Trucks to Accelerate Transition to a Clean-Transportation Future." www.epa.gov/newsreleases/biden-harris-administration-proposes-strongest-ever-pollution-standards-cars-and.

[17] ACEEE. 2023. "Biden's Strong Car and Truck Standards Should Go Even Further." www.aceee.org/press-release/2023/04/bidens-strong-car-and-truck-standards-should-go-even-further.

[18] C2ES. 2023. "U.S. State Clean Vehicle Policies and Incentives." www.c2es.org/document/us-state-clean-vehicle-policies-and-incentives/.

[19] Borlaug et al. 2021. "Heavy-Duty Truck Electrification and the Impacts of Deport Charging on Electricity Distribution Systems." www.nature.com/articles/s41560-021-00855-0.

[20] Nadel. 2022. "Electrifying Trucks and Other Fleets: Utility Infrastructure Will Be Critical." www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2022/6-energy-efficient-and-low-carbon-mobility-for-all/electrifying-trucks-and-other-fleets-utility-infrastructure-will-be-critical/.

of investing in this infrastructure.[21] Likewise, quite a few transit and school systems are committing to purchase electric buses as vehicles need to be replaced,[22] but ultimately most transit and school systems will need to take these steps. For example, the California Air Resources Board has set a goal for public transit agencies to gradually transition to 100% zero-emission bus fleets by 2040.[23] Likewise, Maryland and New York State both have set requirements for all new school buses to be zero emission, with substantial funding to back this up.[24] Other states should look into following these leaders.

In summary, incentives, emissions standards, zero-emissions vehicle requirements, and the build-out of charging infrastructure will all help to grow the EV market. Ultimately, most of the market can be electrified through a combination of these polices, particularly zero-emissions vehicle requirements as well as continued technology and production improvements to lower EV costs so that ultimately EVs are less expensive to purchase and operate than conventional vehicles.

However, while electrifying the transportation sector will be critical to make progress on carbon emissions, policymakers should ensure that EV investments emphasize efficient vehicles[25] and do not come at the expense of other low-carbon transportation policies (e.g., public transit and strategies to enable alternatives to cars) that will help meet climate goals, while also reducing congestion and creating accessible and affordable transportation systems for all.

Planes, trains, ships, and perhaps trucks traveling more than about 500 miles in a trip will be hard to electrify; we discuss these near the end of this brief.

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[21] St. John. 2023. "EV Trucks and Buses Need Costly Grid Updates. Should Utilities Pay?" www.canarymedia.com/articles/clean-fleets/ev-trucks-and-buses-need-costly-grid-updates-should-utilities-pay.

[22] Nadel and Heuther. 2021. *Electrifying Trucks: From Delivery Vans to Buses to 18-Wheelers*. www.aceee.org/research-report/t2102 . St. John. 2023. "How U.S. School Buses Are Going Electric, in Four Charts." www.canarymedia.com/articles/electric-vehicles/how-us-school-buses-are-going-electric-in-four-charts?utm_campaign=canary&utm_medium=email&_hsmi=258328445&_hsenc=p2ANqtz--uNfTGWH2HUZCZncrSIrKCWvZx1pMgXm_Thp37hcc3UXvEqySJ3IaDkTigXZ9_MqouLMfD5aW7hR9GjdGt4TNfW2A8rA&utm_source=newsletter.

[23] CARB. 2018. "California Transitioning to All-Electric Public Bus Fleet by 2040." ww2.arb.ca.gov/news/california-transitioning-all-electric-public-bus-fleet-2040.

[24] Peetz. 2019. "Legislature Passes Electric School Bus Mandate; Montgomery Looks into Testing." https://moco360.media/2019/04/10/legislature-passes-electric-school-bus-mandate-montgomery-looks-into-testing/. NYSERDA. 2023. "Electric School Buses." www.nyserda.ny.gov/All-Programs/Electric-School-Buses.

[25] Heuther. 2022. "9,000-Pound Electric Hummer Shows We Can't Ignore Efficiency of EVs." www.aceee.org/blog-post/2022/06/9000-pound-electric-hummer-shows-we-cant-ignore-efficiency-evs.

Single-Family Homes

ACEEE has found that installing efficient electric heat pumps for space and water heating at the time existing equipment reaches the end of its life will have a lower lifecycle cost for most U.S. homes than installing furnaces and boilers and burning low-carbon fuels (such as biogas and "green" hydrogen [hydrogen produced from emissions-free electricity]). This assumes the use of cold-climate heat pumps in areas with more than about 4,500 heating degree days (e.g., Washington, DC, today and farther north). Space and water heating account for most home use of fuels and thus should be a primary focus of home electrification efforts.[26]

The economics of heat pumps are better in the South than the North due to lower heating needs and lower electricity prices in the South.[27] The South also has a lot of electric resistance heat that can be replaced with heat pumps, reducing energy use and costs as well as high winter peak demand during cold spells such as in Texas in 2021.[28] Electric resistance heat for buildings is inefficient and should generally be avoided.

As much as possible, building shells should be upgraded before or when installing heat pumps for both economic and comfort reasons. Recent ACEEE analyses find that improving building shells will both improve heat pump economics and reduce the costs of moving toward 100% clean power.[29] And weatherizing homes will allow heat pumps to better serve heating loads in cold weather and will improve resident comfort. Home upgrade programs should seek to understand when existing central air conditioners and furnaces will need replacement and target these homes for envelope improvements before existing equipment needs to be replaced, making it easier to switch to a heat pump when existing equipment is replaced.

The IRA includes more than $4 billion for rebates for electrification measures, to be administered by states, and also includes a 30% federal tax credit up to $2,000 for heat

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[26] We have not examined the economics of residential cooking since this is a small energy user and carbon emitter. Decisions on electrifying cooking will depend on cooking preferences, how health concerns are resolved, and the economics of retaining gas service after space and water heating are electrified.

[27] Nadel and Fadali. 2022. *Analysis of Electric and Gas Decarbonization Options for Homes and Apartments*. www.aceee.org/research-report/b2205.

[28] Nadel et al. 2023. *Energy Efficiency and Demand-Response: Tools to Address Texas' Reliability Challenges: Summary*. www.aceee.org/white-paper/2023/05/energy-efficiency-and-demand-response-tools-address-texas-reliability.

[29] Specian. 2023. *Empowering Electrification through Building Envelope Improvements*. www.aceee.org/topic-brief/2023/07/empowering-electrification-through-building-envelope-improvements. Specian. 2023. *Energy Efficiency in a High Renewable Energy Future*. www.aceee.org/research-report/u2303.

pumps and up to $1,200 for heat pump water heaters.[30] Some states and utilities are offering programs to encourage electrification, particularly on the West Coast and in the Northeast.[31] More states and utilities should consider following suit. Some states and cities are starting to pursue building codes that require zero net energy use or zero net carbon emissions,[32] and some (i.e., New York State[33]) are starting to restrict the use of gas in new construction. Given the favorable economics of serving efficient new homes with heat pumps,[34] more jurisdictions should consider these steps.

Several other trends may aid electrification, such as increased use of ductless heat pumps to provide cooling in the north as well as supplementary heating, a growing number of states and utilities phasing out incentives for gas furnaces,[35] and rising costs of gas service in some areas due to expensive pipe replacement programs.[36]

Still, in areas with high electricity prices, the economics of space heating with heat pumps can be challenging in existing homes while inexpensive fossil gas continues to be available.[37] A forthcoming ACEEE report will discuss how electric rates can be redesigned to lower electric bills for households as they shift to heat pumps. For example, Maine has adopted such rates;[38] more states should consider rate designs that will improve heat pump

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[30] Ungar and Nadel. 2022. *Home Energy Upgrade Incentives: Programs in the Inflation Reduction Act and Other Recent Federal Laws*. www.aceee.org/policy-brief/2022/09/home-energy-upgrade-incentives-programs-inflation-reduction-act-and-other.

[31] Cohn and Esram. 2022. *Building Electrification: Programs and Best Practices*. www.aceee.org/research-report/b2201.

[32] NBI. 2023. "Zero Energy/Carbon Codes." https://newbuildings.org/code_policy/zero-codes/.

[33] Phillips. 2023. "N.Y. Ditches Gas Stoves, Fossil Fuels in New Buildings in First Statewide Ban in U.S." www.washingtonpost.com/climate-environment/2023/05/03/newyork-gas-ban-climate-change/.

[34] Tan et al. 2022. *The Economics of Electrifying Buildings: Residential New Construction*. https://rmi.org/insight/the-economics-of-electrifying-buildings-residential-new-construction/.

[35] CPUC. 2023. "CPUC Reduces Incentives for Natural Gas to Better Align with State's Climate Goals." www.cpuc.ca.gov/news-and-updates/all-news/cpuc-reduces-incentives-for-natural-gas-to-better-align-with-state-climate-goals-2023. Walton. 2023. "Colorado Sets Building Electrification Goals for Xcel Energy, Phases Out Subsidies for Some Gas Appliances." www.utilitydive.com/news/colorado-puc-xcel-building-electrification-goals-gas/651739/?utm_source=Sailthru&utm_medium=email&utm_campaign=Issue:%202023-06-01%20Utility%20Dive%20Newsletter%20%5Bissue:50953%5D&utm_term=Utility%20Dive.

[36] Nadel. 2023. *Impact of Electrification and Decarbonization on Gas Distribution Costs*. www.aceee.org/research-report/u2302.

[37] Nadel. 2016. *Comparative Energy Use of Residential Furnaces and Heat Pumps*. www.aceee.org/research-report/a1602.

[38] Ogrysko. 2022. "How New Electric Rates for Mainers Using Heat Pumps or Electric Vehicles Will Work." www.mainepublic.org/environment-and-outdoors/2022-10-13/how-new-electric-rates-for-mainers-using-heat-pumps-or-electric-vehicles-will-work.

economics while following rate design principles. Adding a price on carbon (which will affect fuel prices) is another option, as is now happening in California and Washington and will soon start in New York State. Financing (e.g., grants for low-income households, loans for others) will be needed to help homeowners pay the capital costs of electrification. As some customers electrify and leave the gas system, gas rates will rise as fewer customers will remain to cover gas system fixed costs.[39] It will be important to provide grants or other assistance so that low-income customers can electrify and not be stuck with rising gas rates. ACEEE, as part of our dedication to achieve equitable outcomes, will advocate for supportive policies that will not exacerbate cost burdens on low-income households in the electrification transition. Regarding grants, since there are presently about 26 million households now using fossil fuels with income under 80% of their area median[40] and if conversion costs an average of $20,000 per home relative to replacing current equipment at end-of-life (a rough ballpark including all gas appliances as well as in-home electric service upgrades in some homes), needed funding is roughly $500 billion (including multifamily).

Continued heat pump development is needed to reduce costs and improve heat output and efficiency at very low temperatures. Air-to-water heat pumps, now widespread in Europe,[41] need to be brought to market in the United States to help serve homes with hot-water heat distribution systems. Several utilities are piloting street-based ground-source heat pumps where a ground-source network is installed on individual streets using existing utility right-of-ways; [42] these pilots should be scaled up if initial results are promising.

The growing number of incentives and programs will help increase electric heat pump market share, but in order to electrify most homes, in the medium- and long-term, clean heat standards should be considered that require gradually growing shares of heat to be decarbonized (Colorado and Vermont have such policies[43]). Other options include building performance standards for homes, as have been enacted in France,[44] and limitations on sales

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[39] Nadel. 2023. *Impact of Electrification and Decarbonization on Gas Distribution Costs*. www.aceee.org/research-report/u2302.

[40] DOE. 2023. "Low-income Energy Affordability Data Tool." www.energy.gov/scep/slsc/lead-tool.

[41] Wolf. 2023. "Air-to-Water Heat Pumps." www.wolf.eu/en-de/advice/heat-pump/air-to-water-heat-pump.

[42] E.g., Eversource. 2023. "Networked Geothermal." www.eversource.com/content/residential/save-money-energy/clean-energy-options/geothermal-energy. Also, in New York State, the Utility Thermal Energy Networks and Jobs Act requires each utility in the State to do 1–5 pilots and sets the stage for a regulatory proceeding on how to scale up this model across the state.

[43] Colorado PUC. 2022. "Learn About Clean Heat Plans." https://puc.colorado.gov/cleanheatplans. Gallucci. 2023. "Vermont Is Moving from Fuel Oil to Clean Heat." www.canarymedia.com/articles/fossil-fuels/vermont-is-moving-from-fuel-oil-to-clean-heat.

[44] Nadel and Hinge. 2023. *Mandatory Building Performance Standards: A Key Policy for Achieving Climate Goals*. www.aceee.org/research-report/b2303.

of new fossil-fueled equipment, starting with new construction (as discussed above) and ultimately for replacement equipment as is happening now in San Francisco, the Netherlands, and Germany.[45]

Multifamily Buildings

For apartments with a separate heating system for each apartment, ACEEE has found that the system types and economics are broadly similar to those for single-family homes. But conversion to heat pumps can be expensive for apartments served by a central gas or oil boiler.[46] Conversion options include a central chiller heat pump that replaces an existing boiler or installation of ductless heat pumps or variable refrigerant flow (VRF) systems that are alternatives to boiler systems. The multifamily sector, particularly high-rise buildings, may be the most challenging sector to electrify from a technical and cost perspective. Some conversions have been done,[47] but we need to gain much more experience on where high-rise conversions make sense and where use of decarbonized fuels will be a better option. Technical assistance, financing, and grants will all be needed, particularly for affordable rental units, which are the source of housing for the majority of low-income households in the United States.[48] Where tenants pay for heating and hot water, building owners have little incentive to invest in new systems unless changes are either mandated or funded (multifamily is included in the $500 billion cost discussed in the previous section). Ultimately, clean heat standards (discussed in the prior section) and/or building performance standards that steadily ramp-up to zero net carbon emissions (discussed in the next section) can help push efficient decarbonization, including electrification.

Commercial Buildings

Commercial buildings can often use heat pumps for space and water heating, such as rooftop heat pumps for low-rise buildings and chiller heat pumps for larger buildings. The economics of heat pumps can be challenging when electricity costs are high and fuel costs

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[45] Baker and Bloomberg. 2023. "A Major Metro Area Just Declared War on Gas Appliances — but Not Stoves." https://fortune.com/2023/03/15/san-francisco-gas-appliances-ban-stoves/. CE Delft. 2022. *The Natural Gas Phase-Out in the Netherlands*. https://ce.nl/wp-content/uploads/2022/04/CE_Delft_210381_The_natural_gas_phase-out_in_the_Netherlands_DEF.pdf. Rosenow. 2023. "Germany Wants to Phase Out Fossil Fuel Heating. What Does the New Law Say?" www.eceee.org/all-news/columns/germany-wants-to-phase-out-fossil-fuel-heating-what-does-the-new-law-say/.

[46] See note 27.

[47] Elevate. 2023. "Case Study: Building Electrification at Madison's Zoe Bayliss House." www.elevatenp.org/publications/case-study-building-electrification-at-madisons-zoe-bayliss-house/.

[48] Census. 2023. "Low-Income Renters Spent Larger Share of Income on Rent in 2021." www.census.gov/library/stories/2023/03/low-income-renters-spent-larger-share-of-income-on-rent.html.

are low.[49] And with larger systems, a small amount of supplemental fuel-based heat may be needed when outdoor temperatures get low (another option is storage of hot water).[50] For rooftop units, additional development work is needed to reduce costs and hopefully improve performance as well. Chiller heat pumps are becoming more common in Europe, but limited U.S. applications to date are generally served by imported equipment. Some manufacturers are starting to produce these units in the United States. Other manufacturers can seek funding to start production under the IRA-funded 48C tax credit and Defense Production Act.[51]

For new construction, costs can often be reduced with high-efficiency design and construction that minimize heating and cooling needs and then serve these needs with heat pumps, avoiding the cost of providing gas service to a building.[52]

For existing buildings, a growing number of cities and states are adopting mandatory building performance standards that gradually ramp down to zero net carbon emissions.[53] Equipment manufacturers tell us that demand for heat pumps is growing in these jurisdictions since equipment installed today will often be operating in the 2040s when zero emissions standards take effect in some jurisdictions. More jurisdictions should consider such standards, potentially with assistance from the IRA-funded U.S. Department of Energy (DOE) zero energy codes program.[54] To help building owners meet these standards, there will be a need for technical and financial assistance from cities and states are well as local utilities.[55]

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[49] Nadel and Perry. 2020. *Electrifying Space Heating in Existing Commercial Buildings: Opportunities and Challenges*. www.aceee.org/research-report/b2004.

[50] EPRI. 2018. "First Person—Electric University." https://eprijournal.com/wp-content/uploads/2018/05/First-Person_Electricdf.pdf.

[51] IRS. 2023. "IRS and Treasury Provide Guidance on the Qualifying Advanced Energy Project Credit." www.irs.gov/newsroom/irs-and-treasury-provide-guidance-on-the-qualifying-advanced-energy-project-credit. Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization. 2023. "DOE Heat Pump Defense Production Act Program." https://energycommunities.gov/funding-opportunity/doe-heat-pump-defense-production-act-program/.

[52] USGBC Massachusetts. 2019. *Zero Energy Buildings in Massachusetts: Saving Money from the Start*. https://builtenvironmentplus.org/zero-energy-buildings/.

[53] See note 44.

[54] Nadel. 2023. "The Energy Department Can Help Cities and States Steer Existing Buildings to Net Zero." www.aceee.org/blog-post/2023/04/energy-department-can-help-cities-and-states-steer-existing-buildings-net-zero.

[55] Nadel. 2020. *How Energy Efficiency Programs Can Support Building Performance Standards*. www.aceee.org/topic-brief/2020/10/how-energy-efficiency-programs-can-support-building-performance-standards.

Industry

In industry, fossil fuels are the primary source of process heating, accounting for over 40% of industrial carbon emissions. Fossil fuels are also an important feedstock for chemical production. For process heating, current industrial heat pump (IHP) technologies can replace fossil fuels in many low- and medium-temperature applications (up to about 160°C/330°F presently), with products in development able to go up to about 280°C/535°F.[56] Where possible, processes should be redesigned to allow lower process temperatures. IHP systems are becoming more common in Europe, driven by climate concerns and an imperative to reduce dependence on gas from Russia.[57] Research and development (R&D) will be needed to commercialize higher temperature heat pumps and to better understand how to implement IHP in process operations.

In the United States, ACEEE and our partners are starting an initiative to make widespread use of IHPs, including encouraging domestic production, implementation of demonstration projects, launching utility programs, and developing awareness within industry of IHP opportunities, supported by a variety of federal programs and policies.[58] As with commercial heat pumps, the IRA-funded 48C and Defense Production Act programs will help fund production lines to produce IHP systems and, in the case of 48C, some IHP installations. The amount of funding is limited, so additional funding from Congress will be important, as will widespread utility efforts to promote these systems to industrial customers.

For many applications above 280°C/535°F but below roughly 1,000°C/1,830°F, other electric heating technologies such as infrared, induction, and electric resistance can often be more efficient than hydrogen given the inefficiencies in hydrogen production and combustion,[59] not to mention nitrogen oxide emissions associated with hydrogen combustion.

As industry electrifies, energy storage, load management and other techniques will become increasingly important for matching factories' electricity demand with clean electricity supply

[56] Zuhlsdorf et al. 2019. "Analysis of Technologies and Potentials for Heat Pump-Based Process Heat Supply above 150 °C." www.sciencedirect.com/science/article/pii/S2590174519300091.

[57] Hockenos. 2023. "In Europe's Clean Energy Transition, Industry Looks to Heat Pumps." https://e360.yale.edu/features/europe-industrial-heat-pumps.

[58] ACEEE. 2023. "Industrial Heat Pump Collaboration Aims to Reduce Costs and Greenhouse Gas Emissions in U.S. Industries." www.aceee.org/press-release/2023/07/industrial-heat-pump-collaboration-aims-reduce-costs-and-greenhouse-gas.

[59] Barnard. 2023. "Industrial Heat Will Decarbonize with Electricity, Not Molecules, & Kanthal SVP Helps Us Understand Why." https://cleantechnica.com/2023/03/30/industrial-heat-will-decarbonize-with-electricity-not-molecules-kanthal-svp-helps-us-understand-why/.

and onsite distributed energy resources.[60] Also, loads can be reduced through strategic energy management[61] as well as efforts to reduce use of energy-intensive materials (e.g., steel and concrete), such as through building codes that incorporate the embodied carbon in building materials.[62]

While the efforts discussed here will increase electrification of industry, getting to 90% electrification will not be easy. Some companies will do this as part of their sustainability goals, but ultimately some combination of customer demand for low-carbon products and future carbon pricing, supported by regulations, will be needed to encourage investments in decarbonization.

Power Sector

The power sector will also need to decarbonize through increased carbon-free electricity generation (e.g., renewable and nuclear power) as well as some power generated with "green" hydrogen and some with natural gas coupled with carbon capture and either utilization or storage. Other experts discuss some of the pathways to get there.[63]

Electrifying 90% of fossil fuel use will increase electricity consumption requiring additional generation, transmission, and distribution system investments. For EVs, much of the charging can be during nighttime off-peak periods when generating and distribution capacity is available or during the day at places of employment to take advantage of daytime solar power production.[64] For EVs, buildings, and factories, load management and energy storage will become increasingly important so that power demand and supply can be balanced when demand is high or supplies low.

Generation needs will grow, with much of this power coming from renewable energy systems (solar, wind, and hydro) backed up by batteries, but long-term storage will also be needed for periods when the wind is not blowing, the sun is not shining, or when power demand is particularly high such as during heat waves and polar vortex events. New long-

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[60] Johnson. 2023. *Clean Power for Industry: Unlocking Flexible, Renewable Energy for Industrial Heat Processes*. www.aceee.org/research-report/I23032.

[61] SEMHub. 2023. "What Is SEM?" https://semhub.com/what-is-sem.

[62] Esram and Hu. 2021. *Knowledge Infrastructure: The Critical Path to Advance Embodied Carbon Building Codes*. www.aceee.org/white-paper/2021/12/knowledge-infrastructure-critical-path-advance-embodied-carbon-building-codes.

[63] Net-Zero America. "Net-Zero America: Potential Pathways, Infrastructure, and Impacts." https://netzeroamerica.princeton.edu/?explorer=year&state=national&table=2020&limit=200.

[64] Needell et al. 2023. "Strategies for Beneficial Electric Vehicle Charging to Reduce Peak Electricity Demand and Store Solar Energy." www.sciencedirect.com/science/article/pii/S2666386423000462.

term storage systems are being developed,[65] and research on these systems should be continued. Novel new storage systems are likely to be complemented by projects that produce green hydrogen when more renewable power is available than is needed, and then burning this hydrogen in peaking power plants.

Increased transmission will be needed to get clean power to major urban areas and other load demand centers. In addition, distribution systems will need reinforcement at nodes where electrification creates high power demands, such as at factories that electrify substantial loads and truck stops and fleet depots where many electric trucks and buses need to be charged at the same time. On transmission, the current system for approving new lines is onerous and needs to be improved. Congress and the Biden administration are discussing several proposals.[66] While ACEEE does not focus on these issues, we hope that a workable compromise will move forward. On distribution, utilities need to work with their customers and regulators to understand when and where more power is needed and proactively plan distribution system investments to meet these needs.

Hard to Electrify Uses

Hard to electrify uses and alternative paths to compliance are discussed in our 2022 paper.[67] We have recently updated this analysis to include chemical feedstocks and opportunities to use electro-technologies in industry beyond heat pumps. This slightly revised analysis is contained in an appendix to this brief. Hard-to-electrify uses constitute just over 10% of current U.S. energy use. Briefly, in order of the amount of non-electric energy (highest to lowest) that will be required:

Chemical feedstocks: De-fossilization of chemical feedstocks will be essential to reducing industrial carbon emissions. Several pathways exist to accomplish this including a shift to bio-feedstocks, use of green hydrogen, and use of captured CO_2 to replace fossil fuel feedstocks. The best solution will vary from chemical to chemical. Additional R&D and market development will be needed to commercialize these opportunities. ACEEE is working to identify high-value product markets, such as sustainable aviation fuels and cosmetics that could represent the beach head for early deployment of these alternatives. To encourage

[65] Heilbrun. 2022. "Power for 127 Hours: The Economics of Long-Duration Energy Storage." https://environment-review.yale.edu/power-127-hours-economics-long-duration-energy-storage.

[66] Senate Committee on Energy and Natural Resources. 2023. "Manchin Rallies Senators around Bipartisan Permitting Reform Bill." www.energy.senate.gov/2023/5/manchin-rallies-senators-around-bipartisan-permitting-reform-bill. The White House. 2023. "FACT SHEET: Biden–Harris Administration Outlines Priorities for Building America's Energy Infrastructure Faster, Safer, and Cleaner." www.whitehouse.gov/briefing-room/statements-releases/2023/05/10/fact-sheet-biden-harris-administration-outlines-priorities-for-building-americas-energy-infrastructure-faster-safer-and-cleaner/.

[67] See note 7.

purchase of low emissions formulations, "buy clean" efforts by governments at all levels and private companies should be expanded.[68]

Airplanes: Short-distance airplanes can be electric,[69] but beyond about 500 miles, synthetic fuels made from biomass, captured CO_2, and green hydrogen may be the path to decarbonization.[70]

High-temperature process needs in industry: As noted earlier, industrial heat pumps now in development might be able to provide steam at temperatures up to roughly 280°C/535°F and other electric heating technologies such as infrared, induction, and electric resistance can often be more efficient than hydrogen given the inefficiencies in hydrogen production and combustion. For the highest temperatures (above about 1,000°C/1,830°F), low-carbon fuels will often be needed, such as green hydrogen.

Ships: As with airplanes, short-distance ships can use electricity, but fuels will be needed for longer distances. The leading candidates for a decarbonized fuel are ammonia made from green hydrogen[71] or green methanol.[72]

Long-distance trucks: Current electric trucks can go up to 500 miles before recharging (e.g., the Tesla Semi), but for longer distances we will either need improvements to batteries and/or quick battery-swapping systems (now being developed in China[73]). Another option will be hydrogen fuel cells. Several manufacturers are now developing fuel cell trucks (e.g., Nikola and Toyota). Fuel cell vehicles will require the build-out of hydrogen fueling infrastructure.

Supplementary heat for homes, apartments, and large commercial buildings: For very cold climates (above 6,000 heating degree days according to our prior research, e.g., north of Detroit), homes could benefit from a backup fuel rather than require electric resistance heat that will add to winter peak demand. For high-rise multifamily buildings, alternative fuels

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[68] Bluegreen Alliance. 2023. "Buy Clean." www.bluegreenalliance.org/site/buy-clean/.

[69] Bowler. 2019. "Why the Age of Electric Flight Is Finally Upon Us." www.bbc.com/news/business-48630656.

[70] DOE. 2023. "Sustainable Aviation Fuel Grand Challenge." www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge.

[71] Gallucci. 2021. "Why the Shipping Industry Is Betting Big on Ammonia." https://spectrum.ieee.org/why-the-shipping-industry-is-betting-big-on-ammonia.

[72] Paris. 2023. "Methanol Takes Lead in Shipping's Quest for Green Fuel." www.wsj.com/articles/methanol-shipping-green-fuel-11675445221.

[73] Yukun. 2023. "Battery Swapping Key for Heavy-Duty Trucks." www.chinadaily.com.cn/a/202301/18/WS63c74916a31057c47ebaa452.html.

(e.g., biogas) may be a lower-cost path to decarbonization than electrification.[74] And some commercial buildings may need back-up heat to supplement heat pumps when thermometers plunge.[75] We see biofuels as the leading candidate to serve these loads as biofuels can generally be used in existing pipes and burners without modifications.

Rail: As with planes and ships, battery-electric engines can cover short distances, but for longer distances either tracks will need to be electrified (expensive and therefore viable on only some lines[76]), or an alternative fuel will be needed, such as hydrogen.[77]

For these hard-to-electrify sectors, research, development, and demonstrations (RD&D) on the many possible paths forward need to be accelerated. In some cases, such as long-distance trucks and multifamily buildings, this RD&D may determine that electrification is a viable option, but for others we will need to pursue alternative fuels, often based on hydrogen.

Conclusion

Electrification of about 90% of our current energy needs is possible and needed to reduce carbon emissions while also often reducing consumer costs and improving health. As ACEEE Senior Manager Michael Waite recently found, the United States has steadily increased the electric share of all energy use from 1950–2010, but since 2010 this trend has slowed (figure 1). As a nation, we need to get back on our earlier pathway and then accelerate efforts many-fold since electrification is a critical strategy for decarbonization as well as improving energy efficiency and reducing emissions of pollutants released when fossil fuels are burned.

[74] See note 27.

[75] See note 49.

[76] Marsh. 2021. "Is Electrifying the Freight Rail Network Cost Prohibitive?" www.freightwaves.com/news/is-electrifying-the-freight-rail-network-cost-prohibitive.

[77] Patel and Bloomberg. 2021. "A Hydrogen-Powered Train Will Make Transport History as Europe Looks to Become World Leader in Green Rail Travel." https://fortune.com/2021/04/23/hydrogen-train-transport-europe-green-rail/.

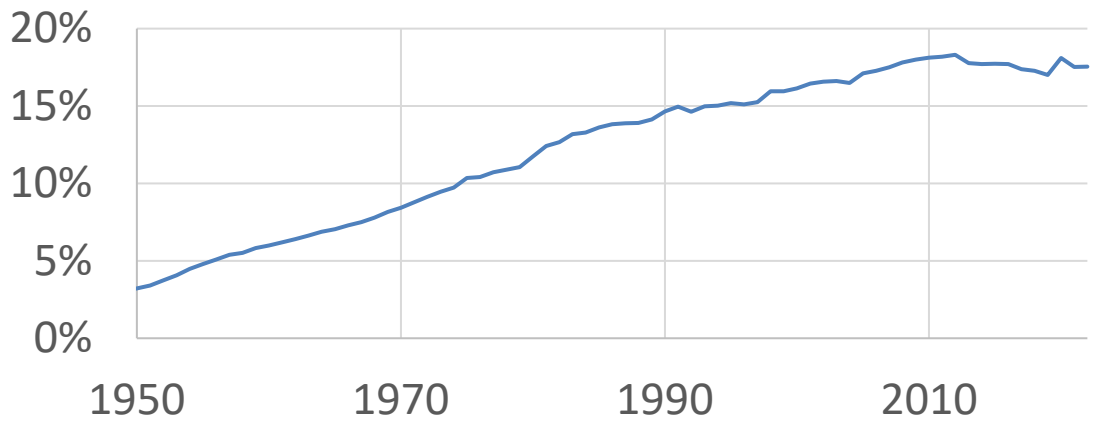

Figure 1. Percentage of end-use energy from electricity (total across residential, commercial, industry, transportation). Source: Analysis by Michael Waite, ACEEE, of data in EIA Monthly Energy Review.[78]

Recent federal IRA funding will help, but many more actions will be required. Utilities and regulatory commissions should expand efforts to promote electrification in applications they deem appropriate and carefully examine rate structures and utility investment guidelines to seek strategies that promote electrification and lower costs. Cities and states should understand the needs in their jurisdictions and develop local programs and policies that move toward decarbonization, including vehicle emission standards, new zero net energy or zero net carbon building codes, building performance standards for existing buildings, and clean heat standards. Businesses and homeowners should evaluate electric options when new equipment needs to be purchased, and companies that produce vehicles and building equipment should expand their electric product offerings. And the federal government needs to improve transmission approvals, fund RD&D, and help fund efficiency and electrification retrofits to affordable housing. Ultimately, if we are to electrify 90% of U.S. energy use, we need to use current efforts to build support, but steadily reducing emissions will often require regulations, such as clean heat and building performance standards and/or restrictions on the installation of new fossil-fired equipment. If these steps are taken, the United States can decarbonize while also improving resident well-being and building a strong economy.

[78] EIA. 2023. *Monthly Energy Review*. "Total Energy." www.eia.gov/totalenergy/data/monthly/index.php.

Appendix – Analysis of Hard-to-Electrify Uses

This analysis is explained in detail in our 2022 paper.[79] A summary of this analysis is contained in the table below, including a few refinements not in the earlier analysis. Changes relative to the earlier analysis are all shown in *italics*.

Table A1. Approximate Amount of Energy Needed in the U.S. in 2040 from Decarbonized Fuels

Item	Annual Energy Use (quads)	% Needing Fuels	Explanation	Annual Fuel Needed (quads)	% of Total	Notes
Industrial feedstocks	*6.6*	*75%*	*Efficiency, recycling and product substitution can address roughly 1/4 of current use.*	*4.98*	*40%*	*Guess, subject to a large amount of uncertainty*
Long-distance planes	3.7	87.5%	Over 500 miles	3.25	26%	% over 500 miles from Bureau of Transportation Statistics 2022.
Industrial high-temp processes	9.8	*15%*	Temperatures over 280° C	1.47	12%	280° C from Zuhldorf et al. 2019. McMillan et al. 2021 find 27% of process heat needs at 300° C and up so we estimate 30% at 280° C. *Of this higher temperature heat, perhaps half can use electric boilers and other electro-technologies, leaving ~15%for fuels.*
Ships	0.9	90%	Rough guess	0.84	7%	Short-distance shipping can be electrified but most cannot -- see Smil 2019
Long-distance trucking	5.3	13%	Over 500 miles	0.69	6%	13% for classes 7 and 8 from Census as cited in Nadel and Huether 2021. This does not include small additional use for classes 3-6 but this is likely to be offset by the fact that regional-hauls are increasing and long-distance hauls as a percentage of the total are declining.
Residential space heating	3.9	12%	Cold climate per RECS * 20%	0.48	4%	Per RECS, 60% of gas, oil and propane heating energy use in areas designated "cold climate." (EIA 2018). In Metro Minneapolis on average cold climate heat pumps reduced winter energy use 65% (Shoenbauer 2017), we raise to 80% as Minneapolis is colder than average for the cold climate area
Rail	0.5	78%	Midpoint of 15-30% range estimated by Blaze and cited in Marsh 2021	0.39	3%	
Commercial space heating	1.9	10%	Per case studies in Nadel and Perry 2020	0.19	2%	
Total	32.71			12.29	100%	
				38%	of fuel use	
				12%	of total use	

Source: Nadel 2022. See note 7. The only changes are the addition of the industrial feedstock row and a 50% reduction in the amount of fuels needed for industrial process heat. The other half of process heat can be handled with electric boilers, and infrared, ultraviolet, ultrasonic, and other electro-technologies.

[79] See note 7.