Electric Buildings

Repowering homes and businesses for our health and environment

ENVIRONMENT AMERICA
RESEARCH & POLICY CENTER

U.S. PIRG Education Fund

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Executive summary

To prevent air and water pollution and avoid the worst impacts of global warming, America must move toward meeting our energy needs with 100% renewable energy. Getting there will require that we get the most out of every bit of energy we use — and that we stop burning fossil fuels in our homes and commercial buildings.

Wind and solar power are rapidly replacing dirty fossil fuels like coal as leading sources of our electricity.[1] As our electricity grid becomes cleaner, replacing the direct burning of gas, heating oil and propane in our buildings with electricity will reduce pollution of our air, land and water from fossil fuel production and use.

New and improved technologies are putting clean, efficient electric space heating and water heating, and electric appliances like stoves within the reach of most American households. Analysis shows that electrifying the vast majority of America's residences and commercial spaces by 2050 could reduce net greenhouse gas emissions from the residential and commercial sectors by about 306 million metric tons of carbon dioxide (CO_2) in 2050.[2] That is the equivalent of **taking about 65 million of today's cars off the road** — almost three times the number of vehicles in Texas.[3]

Common barriers, including knowledge gaps, high upfront costs and lack of governmental support, often make the decision to switch from fossil fuels to electricity challenging for many homeowners, tenants and businesses. Local, state and federal governments should adopt policies to help overcome those barriers and accelerate the transition of our homes and businesses away from fossil fuels and toward electric power.

Fossil fuel burning in homes and businesses contributes to global warming and puts our health and safety at risk.

- There are almost 140 million housing units in the United States, and 5.6 million commercial buildings.[4] Three out of every four American homes use fossil fuels directly for space heating, water heating or appliances.[5] Direct burning of fossil fuels accounts for more than half of all energy used in homes and at least 34% of all energy used in commercial buildings.[6] These tens of millions of housing units and millions of commercial buildings will eventually need to be electrified.
- In 2018, fuel combustion in U.S. homes and businesses produced 590 million metric tons of CO_2 equivalent, accounting for almost 9% of total U.S. greenhouse gas (GHG) emissions.[7]
- Burning fossil fuels within our homes creates indoor and outdoor air pollution, which contributes to the development of respiratory diseases, heart disease and cancer.[8] Air pollution has also been associated with increased risk of contracting and dying from infectious diseases including COVID-19.[9]
    - A 2020 literature review found that, even without considering other direct uses of fossil fuel in homes, "gas stoves may be exposing tens of millions of people to levels of air pollution in their homes that would be illegal outdoors under national air quality standards."[10]
- Extracting and transporting fossil fuels for home use also carries risk. In just the last 20 years, there

have been more than 5,000 incidents involving gas leaks, facility emergencies or other events deemed significant by the operator.[11] These incidents have killed hundreds of people and injured more than 1,000.[12]

Electrifying America's buildings will help the environment and help break our dependence on fossil fuels.

- Switching to electricity to power the vast majority of our homes and businesses by 2050 could cut around 306 million metric tons of CO_2 annual emissions in 2050, according to analysis of modeling data from the National Renewable Energy Laboratory (NREL).[13] These savings are relative to a business-as-usual reference scenario in which there is no support for, or widespread adoption of, electrification technologies.
- These savings are the equivalent of taking almost 65 million of today's passenger vehicles off the road.[14]
- By simultaneously switching to zero-emission renewable electricity, the emission reductions associated with electrification grow to 416 million metric tons of CO_2 in 2050.[15]
- New York, California and Texas are the states with the largest projected decrease in emissions, followed by Illinois, Ohio and Pennsylvania.[16]
- Electrifying buildings also eliminates the health risks posed by indoor combustion of fossil fuels.
- Analysis of the same NREL modeling data shows that switching to electricity to power the vast majority of our homes and businesses by 2050 could reduce consumption of gas by upwards of 7 trillion cubic feet in that year relative to a reference scenario — the equivalent of 82% of all the gas consumed in those sectors in 2019.[18]
    - Reducing our usage of gas also reduces the numerous harmful environmental impacts that occur during its life cycle, including usage of toxic chemicals, contamination of drinking water, overuse of freshwater, methane pollution, and the destruction of natural landscapes.[19]
    - New York, California and Illinois top the list for greatest projected reduction in gas usage, according to the analysis, followed by Pennsylvania, Ohio and Texas.[20]

TABLE ES-1: TOP 10 STATES FOR 2050 EMISSION REDUCTIONS IN BUILDING ELECTRIFICATION SCENARIO[17]

State	Reduction in carbon dioxide emissions from fuel use reduction (million metric tons CO_2)	Reduction in total carbon dioxide emissions (million metric tons CO_2)
New York	40.1	35.4
California	34.2	27.4
Texas	21.9	18.3
Illinois	26.8	16.1
Ohio	23.5	13.9
Pennsylvania	24.7	13.7
Michigan	22.0	12.4
Massachusetts	11.4	10.0
New Jersey	16.5	9.5
Florida	8.7	8.2

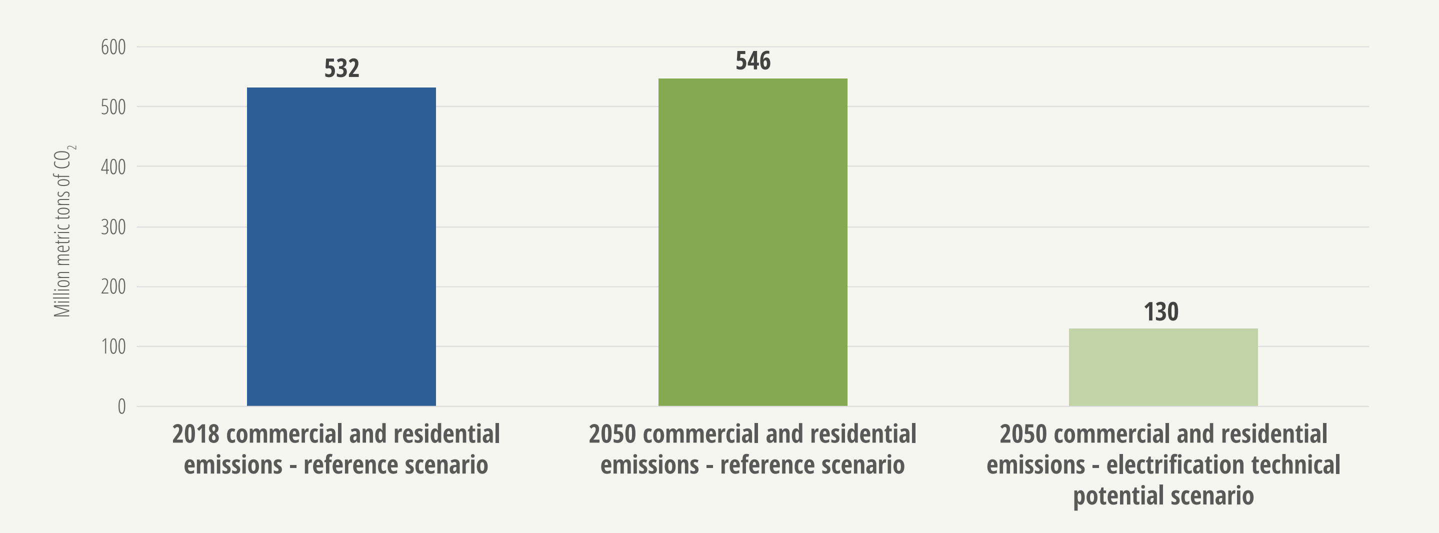

Figure ES-1: Direct carbon emissions from fossil fuel burning in homes and businesses with and without electrification[21]

Electric technologies can repower America's buildings and open the door to renewable energy.

Today's electric technologies can meet nearly all our home and business energy needs — and often do so at a competitive cost and with a fraction of the pollution caused by fossil fuel combustion.

- **Space heating** — Electric heat pumps, which pull heat from the air, ground or from bodies of water and move it around a building, have improved dramatically in recent years.[22] Geothermal heat pumps function well in all climates, and air-source heat pumps can now function efficiently down to -15 degrees Fahrenheit.[23] Air source and geothermal heat pumps are several times more efficient than gas and oil heating systems and can meet both heating and cooling needs in homes and commercial buildings.[24]
- **Water heating** — Electric resistance, heat pump and solar thermal water heaters can all heat water without the direct use of fossil fuels. New technological developments are making electric technologies more efficient and cost-effective. Water heat pumps are often two to three times as efficient as electric resistance water heaters.[25]
- **Appliances** — Highly efficient electric appliances can replace fossil-fueled versions and are often more effective. For example, electric induction cooktops, which cost about as much as a mid-tier gas range, cook faster and are cleaner, more precise and safer.[26]

Building electrification often makes sense for consumers.

- Electric heat pumps are already cost-effective for new construction and for some building retrofits.[27] Rocky Mountain Institute found that customers in 11 different cities across the country could save thousands of dollars over a 15-year period by building all-electric new homes versus mixed-fuel new homes that use fossil fuels for some needs, like space heating and cooking.[28]
- Replacing an existing fossil fuel furnace with an electric heat pump is also financially beneficial in some circumstances.[29] Retrofitting a fossil fuel furnace is most cost-effective when the fuel being replaced is either propane or fuel oil, and when both the furnace and the air conditioning (A/C) unit are at the end of their useful lives.[30]
- Building electrification allows owners to take advantage of falling prices for clean electricity and benefit fully from the installation of solar photovoltaic (PV) panels or subscription to community solar projects.[31] All-electric homes can meet much or all of their energy needs with solar panels — aiding homeowners financially and creating new opportunities for renewable energy.[32]

Common barriers — including lack of knowledge and insufficient incentives — are slowing the electrification of America's buildings.

- Contractors may be unfamiliar with current technology and foster a perception that electric heat pumps and other electric appliances are more expensive, impractical or unreliable.[33]
- Many consumers are not aware of improved technologies for electric heating and cooking — such as advanced heat pumps and induction cooktops — that overcome the limitations of previous generations of electric appliances and are more convenient and safer than fossil fuel-powered options.[34]
- While falling prices have made electric systems affordable and sustainable options for new buildings, the high capital costs associated with retrofitting buildings may mean that electrification is not always financially viable without substantial incentives.[35]
- Fossil fuel systems have long lifetimes, meaning they do not get replaced very often, and any new systems installed in the next few years will last for decades.[36]
- Regulatory barriers like fuel-switching restrictions and unfavorable rate designs make electrification more expensive than necessary. Some states have legacy restrictions on fuel switching that prevent incentivizing electrification in favor of installing gas systems.[37] Utility rate designs that do not incentivize demand response or load flexibility also prevent customers from reaping the maximum benefits of electrifying their buildings.[38] These problems slow the transition to technologies that can be truly zero-emission.[39]
- Concerns about the cost of electrification and about future demand on the grid may lead policymakers to take a "go slow" approach to electrification, despite the long lifetimes of fossil fuel energy systems and the pressing need to move to a 100% renewable energy system no later than mid-century.

Policymakers at the local, state and federal levels should implement policies to accelerate the transition from fossil fuels to clean electricity in our buildings.

- Require all-electric systems in new construction.
- Implement rebate programs, incentives and low-cost financing.
- Implement regulatory solutions, including rate design and fuel-switching regulation changes.
- Create and expand tax incentives for electrified buildings.
- Require building energy transparency and implement building performance standards that limit carbon emissions.
- Educate developers, contractors, retailers and consumers about options for, and benefits of, electrification.
- Update appliance efficiency standards.

Introduction

Renewable energy is on the rise across America. Today, America produces 30 times more solar power than we did in 2010 and three times as much wind energy.[40] Energy from the wind and sun now make up 10% of the nation's electricity supply.[41] Thanks in part to improvements in energy efficiency, in 2018 the amount of energy consumed per capita was 7.8% lower than in 2007.[42] With nearly unlimited potential, falling costs and improving technology, renewable energy is poised to play a leading role in America's energy system.

The growth of renewable energy and advances in energy efficiency couldn't come at a more important time. In order to avoid the worst impacts of climate change, we must virtually eliminate carbon pollution from the burning of fossil fuels by mid-century.[43] Transitioning to an electricity system powered by 100% renewable electricity can help us reach that goal.

But there is a problem. While America's electricity system is increasingly powered by clean energy, the rest of the economy is not. Transportation is still dominated by internal combustion engines and industrial processes still rely heavily on fossil fuels.[44]

The systems we rely on in our homes and businesses are also mostly not electric: tens of millions of buildings across the country rely on the direct burning of fossil fuels — gas, oil and propane — for heat, hot water and to run appliances.[45] Taking full advantage of clean renewable energy in our homes and businesses — and getting to a truly zero-carbon economy — will require that we transition those systems to run on electricity.

Just as with solar and wind energy, technological advances are making a transition to electric homes and businesses easier and more affordable than ever before. New all-electric homes are now less expensive than new mixed-fuel homes in every region of the country.[46] Modern heat pumps can now work effectively in cold climates and electric induction cooking has been shown to be faster and more easily controllable than gas stoves.[47]

The rise of renewable energy and efficient, effective electric appliances and heaters allows us to create a future where all of our buildings run off electricity powered completely by the energy of the wind, the sun and the earth. The path to this future is clear. We have the technology and resources to replace fossil-fueled systems with a clean electric grid that completely powers our lives. With the right policies, support and leadership by government, within a couple decades America can be "all-electric" — and virtually carbon-free.

Electrifying buildings unleashes the potential of clean energy

To clean our air and address global warming, America must move toward 100% clean, renewable energy. The good news is that renewable energy is booming; America gets 30 times as much power from the sun and three times as much power from wind as we did in 2010.[48] Energy from the wind and sun now make up more than 10% of the nation's electricity supply.[49] Seven states and 165 cities nationwide, along with Washington, D.C., and Puerto Rico, have now committed to a future of 100% clean electricity.[50]

But to take full advantage of the potential for clean energy — and to do what is necessary to prevent the worst impacts of global warming — we need to repower everything in our society, including our homes and businesses, with clean energy.

Electrifying our buildings can play a pivotal role in expanding America's reliance on clean, renewable energy and help the nation to address some of its largest challenges.

Cutting global warming pollution

The United States must reduce our use of fossil fuels to prevent catastrophic and irreversible damage to our climate. The Intergovernmental Panel on Climate Change (IPCC) has determined that in order to prevent global temperature rise of greater than 1.5 degrees Celsius the world must reduce CO_2 emissions by at least 45% below 2010 levels by 2030 and reach net-zero carbon pollution by 2050.[51]

To achieve net-zero carbon emissions, America must cut emissions associated with burning fossil fuels in residential and commercial buildings. Electrification of buildings is a key strategy to advance the nation toward an energy system powered by renewable energy.

Direct combustion of fossil fuels in our homes and businesses is bad for our climate. In 2018, fossil fuel combustion in U.S. homes and businesses produced 590 million metric tons of CO_2 equivalent, accounting for almost 9% of total U.S. greenhouse gas emissions and equivalent to the emissions of over 127 million of today's cars.[52] Since 1990, emissions from direct fossil fuel combustion in buildings have stayed relatively constant even as the number of homes and businesses has grown thanks to improvement in energy efficiency.[53] However, emissions from residential and commercial buildings need to fall rapidly and dramatically if the nation is to achieve the emission reductions needed to prevent the worst impacts of global warming. The nation is not currently on track to achieve those reductions.

These emissions figures do not include greenhouse gases emitted in the extraction, processing and transportation of fossil fuels. Methane — the key component of so-called "natural" gas — is up to 84 times more potent a greenhouse gas pollutant than carbon dioxide over a 20-year period, and more than 14 million tons of it were leaked in 2015 throughout the oil and gas supply chain.[55] In recent years, research has revealed higher-than-expected rates of methane leakage.

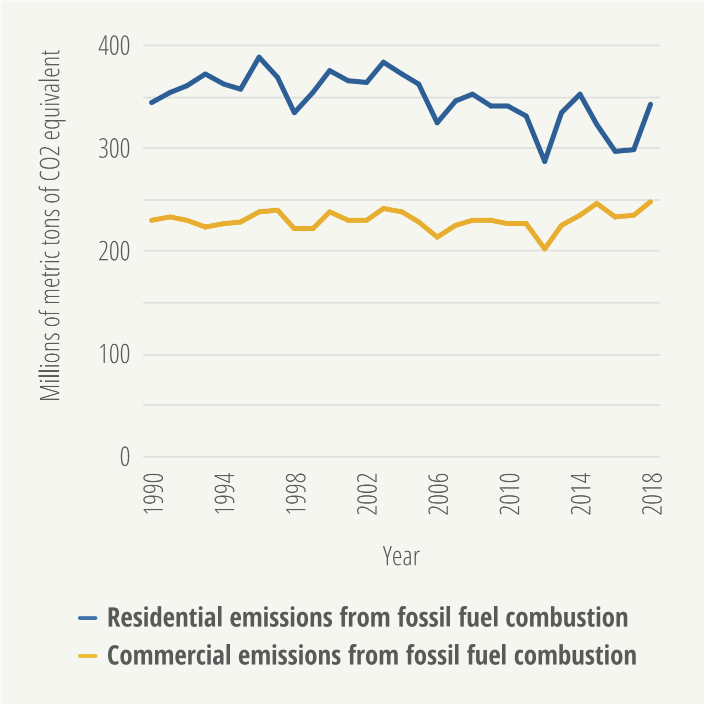

Figure 1: Greenhouse gas emissions from direct fossil fuel combustion in residential and commercial sectors[54]

A recent study looked at five major urban areas on the East Coast and found these urban areas emit more than twice the amount of methane previously estimated by the EPA, with most of these emissions coming from leaks of gas systems in homes and businesses, as opposed to natural sources or landfills.[56] This massive underestimation likely resulted because the EPA includes leaks from the gas distribution system in its estimates, but not leaks from homes and businesses.[57]

By switching to systems powered by electricity, America can stop using fossil fuels that leak and produce carbon pollution and can take full advantage of an increasingly clean electric grid. According to analysis of modeling data from the National Renewable Energy Laboratory (NREL), switching to electricity to power most of our homes and businesses by 2050 would cut around **306 million metric tons of CO_2 annual emissions in 2050** relative to a business-as-usual scenario.[58] That is the equivalent of taking almost 65 million of today's passenger vehicles off the road for a year.[59]

Electric homes and businesses can also help to accommodate more renewable energy on the grid, particularly if they include energy storage, demand-responsive appliances and distributed renewable energy systems like solar panels. (See "Adopting efficiency and other technologies can maximize the benefits of electrification" on page 20.) Demand response, distributed generation and storage have also been shown to reduce strain on the grid at times of peak demand, making widespread electrification easier and lowering costs for ratepayers.[60]

Protecting public health

Building electrification can improve health by reducing outdoor and indoor pollution from fossil fuel combustion. Gas stoves emit a variety of unhealthy gases — such as nitrogen dioxide, carbon monoxide and formaldehyde — that can exacerbate respiratory issues and lead to heart disease and cancer.[61] A study by researchers at the Lawrence Berkeley National Laboratory and Stanford University estimated the effects of gas stoves on indoor air quality in Southern California homes. The study found that in the summer, gas burners add 25%-33% to indoor nitrogen dioxide concentrations and 30% to indoor carbon monoxide concentrations. In the winter, gas burners add 35%-39% to indoor nitrogen dioxide concentrations and 21% to indoor carbon monoxide concentrations.[62] A separate study by the UCLA Fielding School of Public Health found that using a gas stovetop and oven for an hour results in air quality that would be illegal under national outdoor air quality standards, especially in small homes and those without range hoods.[63] These findings suggest that full electrification could help improve indoor air quality for millions of Americans.

The use of fossil fuels in homes and commercial buildings also contributes to outdoor air pollution. There is little regulation on the emissions of fossil-fueled boilers and heaters, and they produce nitrogen oxides, sulfur dioxide and small particulate matter.[64] These pollutants have been found to cause respiratory, cardiac and neurological damage.[65] The authors of the UCLA study also found that gas appliances produce more outdoor nitrogen oxide pollution than the gas-fired power plants in California and a similar amount to all the light-duty vehicles in the state.[66] Another study estimated that 12% of America's urban air pollution from particulate matter was caused by the burning of fossil fuels in buildings.[67]

Air pollution not only causes hundreds of thousands of premature deaths each year in the United States; it can also make us more vulnerable to infectious disease.[68] Recent studies have found that increased levels of air pollution in a community make residents more vulnerable to infection and death caused by diseases like COVID-19.[69]

Even the supply chain to provide fossil fuels to our buildings has negative health effects. Fracking for gas and oil produces harmful air pollution and has the potential to contaminate drinking water.[70] Leakage from gas pipelines not only emits climate-altering methane; it also poses a physical danger to workers and people nearby. Between 2000 and 2019 there have been more than 5,000 incidents involving gas leaks or other events deemed significant by the operator.[71] These incidents have killed hundreds of people and injured more than 1,000.[72]

Electrifying America's homes and businesses can clear our air, protect public safety, reduce the harmful effects of fossil fuels, and make a big contribution toward cutting carbon pollution by enabling us to use clean, renewable energy to serve more of our energy needs.

Fossil fuels power most of our nation's buildings

Until recently, running appliances off electricity was not necessarily more sustainable than directly burning fossil fuels in the home. During the 20th century, highly polluting coal was the dominant fuel for electricity generation.[73] In fact, there was even a large push to run all appliances off gas, as it was viewed as less polluting.[74]

But this is no longer true. The growth of renewable energy has exceeded expectations and the electricity grid is becoming cleaner every year.[75] Outfitting a building to run on electricity allows it to take advantage of an increasingly decarbonized power source. If the future is going to be carbon-free, it will also have to be electric.[76]

In order to achieve net-zero climate pollution by mid-century, our nation will need to electrify millions of buildings that currently are powered by fossil fuels. Fuels described by some as low-carbon alternatives to fossil fuels, like "renewable natural gas," will not suffice because of problems with cost, scalability, and/or continued emissions problems with their use.[77] Additionally, as a modern furnace can have a lifespan of up to 30 years, it is imperative that America phases out the construction of new fossil-fuel projects and begins the enormous task of retrofitting the fossil-fuel infrastructure that already exists.[78]

The following section lays out some of the main end-uses of fossil fuels in homes and commercial buildings. See "Electric technologies can repower America's buildings" on page 16 for electric technologies that can replace the use of fossil fuels in buildings.

Fossil fuel use in homes

Currently three out of every four American homes directly burn fossil fuels for heating, hot water or to fuel appliances, such as gas stoves.[79] More than half of all home energy usage currently comes from burning fossil fuels on-site.[80] In order to reduce our reliance on harmful fossil fuels, we must first understand the ways in which fossil fuels are currently used in our homes and businesses.

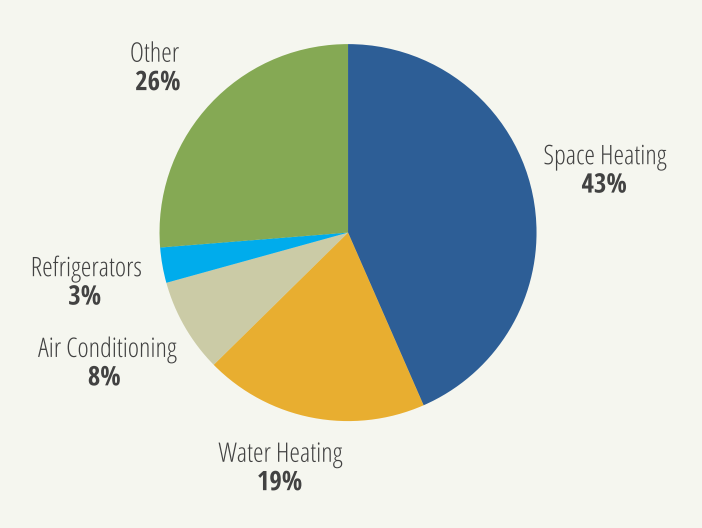

Figure 2: U.S. residential energy consumption in 2015 by percentage of end-use[83]

Sources of fossil fuel use

According to the U.S. Energy Information Administration, energy consumption associated with space heating and water heating accounted for nearly two-thirds of residential energy usage in 2015.[81] Air conditioning and refrigeration accounted for another 8% and 3.3% respectively, with end uses like lighting, clothes washers and dryers, TVs and cooking appliances making up the rest of U.S. residential energy usage.[82]

Together, space heating and water heating account for the highest proportion of energy consumed by U.S. households and both currently rely heavily on fossil fuels. In 2015, around 80% of the energy used for space and water heating in U.S. homes came from the direct burning of fossil fuels.[84]

Central heating by furnaces and boilers, typically reliant on burning gas or heating oil, is the most common way that Americans heat their homes. Some buildings use space heaters distributed around a residential or commercial building – such as gas-fired or electric space heaters, pellet stoves and fireplaces – as primary or secondary sources of heat.[85]

Home heating use varies by region

The fuels used to heat buildings vary by region, resulting in regional differences in opportunities for electrification.

Heating oil and propane – Buildings using fuel oil or propane are great candidates for immediate electrification because they have immense cost-saving and emission-reduction potential. Nationwide, propane is used as a heating fuel by less than 10% of all homes, and fuel oil is only significantly used in the Northeast, which accounts for 85% of the nation's heating oil sales.[86]

Heating oil and propane produce more greenhouse gas pollution than other sources of heat. A case study on the costs and emissions of different heating fuels used in Providence, Rhode Island, for example, found that annual carbon emissions average 17,400 pounds for a home using heating oil, 13,900 pounds for a home using propane and 12,200 pounds for gas. With the current electric grid in Providence, operating an electric heat pump would emit an average of 8,200 pounds of carbon annually, less than half the emissions of heating oil.[87] Unlike fossil fuels, emissions resulting from electric home heating will likely decline over time as the grid becomes cleaner, magnifying the emissions reduction benefits of electrification. That decline in emissions could happen quite rapidly if Rhode Island meets its new goal of generating 100% of their electricity with renewable energy by 2030.[88]

Electrifying homes fueled by heating oil and propane also makes financial sense – even in cold climates like New England. The same study found that over a 15-year period, for new buildings in Providence, electric heat pumps saved a consumer thousands of dollars compared to heating oil and propane.[90]

While households using fuel oil or propane for space heating and water heating account for fewer than 10% of all U.S. households, they produce more than 20% of all carbon emissions from space and water heating.[91] Switching from fuel oil to electricity represents "low-hanging fruit" with immediate cost savings for homeowners and significant emission reductions for the public.

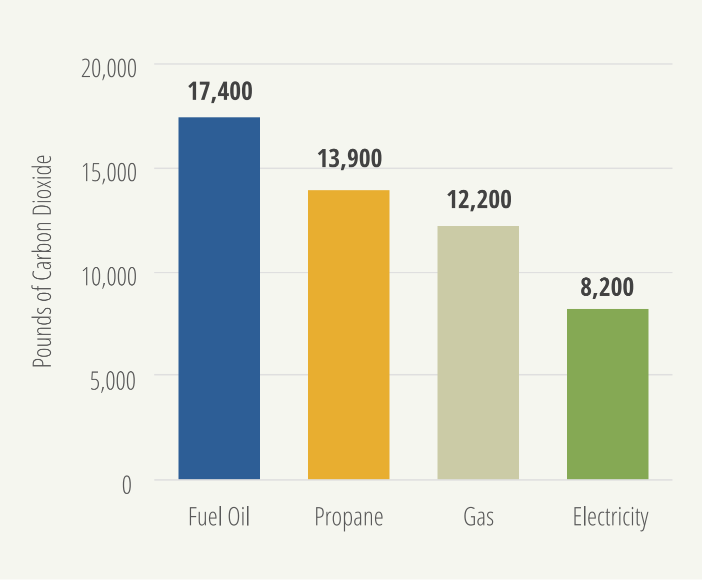

Figure 3: Annual carbon emissions for furnaces in Providence, RI, by fuel source[89]

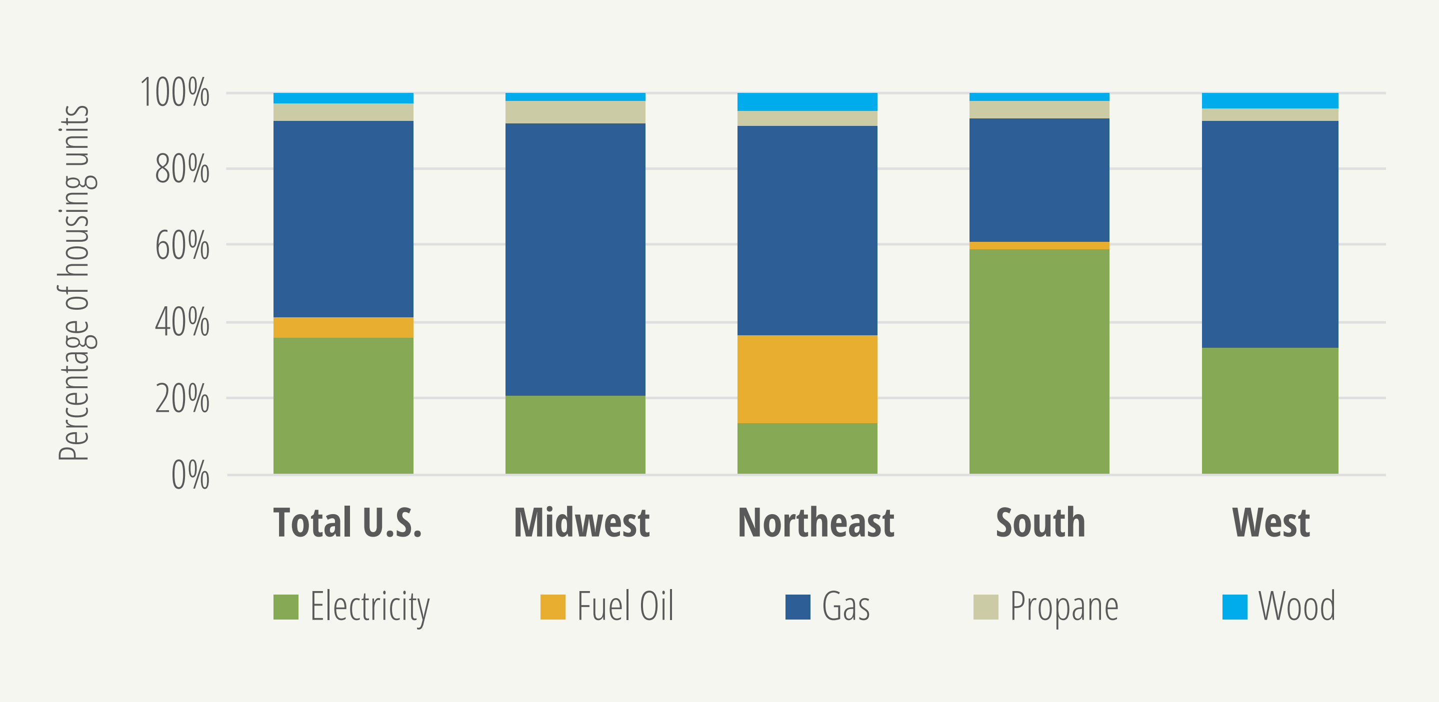

Figure 4: Primary fuel used for residential space heating by region [98]

Gas — Homes and buildings in the West, Midwest and Northeast are more likely to rely on gas for water and space heating.[92] Gas remains a popular heating fuel because of its current low price, and remains the dominant fossil fuel in every region of the country.[93] Gas prices can fluctuate dramatically, however; the highest national average price over the last 15 years was almost four times higher than the lowest.[94] Retrofitting existing buildings powered by gas to run on electricity is not currently cost-effective in much of the country due to system and installation costs and the costs of upgrading the power supply for a building, as well as low gas costs.[95] However, since gas furnaces have lifespans of up to 30 years, new gas furnaces installed today will likely remain in place until 2050, the date by which America must virtually eliminate fossil fuel burning in order to prevent the worst impacts of global warming.[96] As a result, it is critical both to power all new buildings with electricity and to transition to electricity as existing gas furnaces and boilers reach the end of their useful lives.

Electricity — Homes in the South are most likely to entirely power their homes with electricity, as the warmer climate enabled the region to adopt electric heat pumps earlier than other regions. As it is more affordable to heat buildings with electric technologies in warmer and more temperate climates, these areas of the country should be transitioning to electricity faster than other regions. In California, for instance, where constructing a new home with a heat pump saves consumers $2,000 to $3,000 over a gas furnace, several cities have already banned new gas infrastructure.[97]

Water heating in homes

Water heating is the second largest end-use of energy in homes.[99] As with space heating, gas is the most commonly used fuel, propane is not widely used, fuel oil is only significant in the Northeast, and much of the South already heats its water using electricity.[100]

Buildings in the U.S. most commonly rely on conventional tank water heaters, which heat water and store it in a tank for later use. If a conventional tank water heater is not heavily insulated, it is likely to leak a lot of energy. Tanks heated by gas and oil also lose heat due to venting issues, leading to more inefficiency.[101] Tankless or demand-type heaters are an option for consumers, and reduce some of the heat loss that is usually associated with conventional storage water heaters.[102] However, they are much less common than conventional tank water heaters, currently comprising around 3% of water heaters in American homes.[103]

Fossil fuel use in commercial buildings

In 2012, the U.S. Commercial Buildings Energy Consumption Survey found that at least 34% of the energy used in commercial buildings came from direct combustion of fossil fuels.[105] Electricity accounts for a higher proportion of total energy consumption in commercial buildings than in homes, as commercial buildings often have more electric appliances, like computers, printers, telephones and lighting.[106]

However, for space and water heating, commercial buildings still rely heavily on gas.[107] This suggests that commercial building owners should focus on electrifying heating systems and appliances, while also looking to more energy-efficient electric technologies to reduce overall energy usage and impacts on the electric grid. (See "Electric technologies can repower America's buildings" on page 16.)

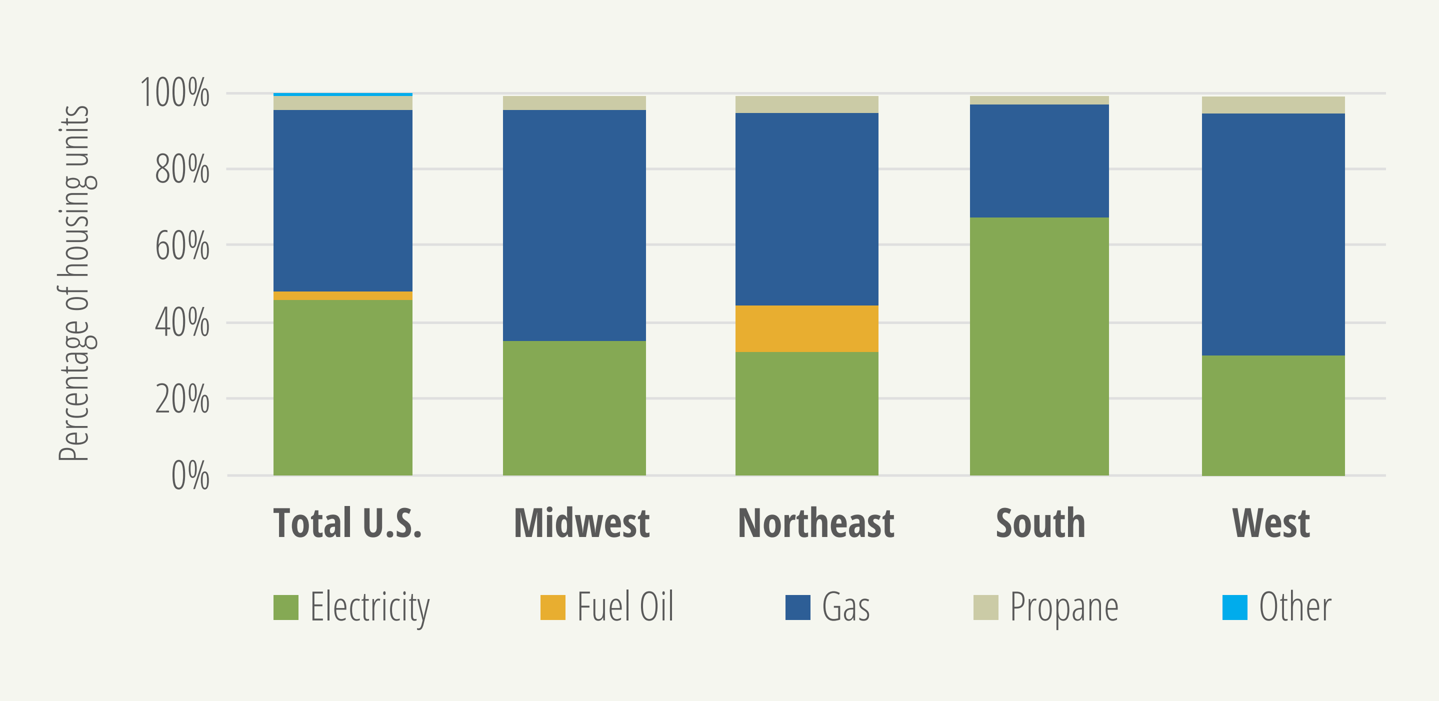

Figure 5: Primary fuel used for residential water heating by region[104]

Electrifying buildings conserves energy and prevents pollution

With almost 140 million homes and 5.6 million commercial buildings in the United States, there is enormous potential for fuel and energy savings, as well as greenhouse gas emissions reductions, from electrifying the building stock in America.[108]

The National Renewable Energy Laboratory's (NREL) *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050* presented possible paths electrification could take in the United States.[109] The study looked at five speeds of electrification technology adoption, including a reference scenario in which there is the least incremental change in electrification and an electrification technical potential scenario in which electrification adoption occurs nationwide starting in 2018 and is slowed only by equipment lifetimes.[110]

TABLE 1: TOP 10 STATES FOR 2050 EMISSION REDUCTIONS IN BUILDING ELECTRIFICATION SCENARIO[114]

State	Percentage of 2017 statewide emissions produced by the residential and commercial sectors	Increased emissions from electricity usage (million metric tons CO_2)	Reduction in carbon dioxide emissions from on-site fuel consumption (million metric tons CO_2)	Net reduction in carbon dioxide emissions (million metric tons CO_2)
New York	34%	4.7	40.1	35.4
California	12%	6.8	34.2	27.4
Texas	3%	3.6	21.9	18.3
Illinois	18%	10.7	26.8	16.1
Ohio	13%	9.6	23.5	13.9
Pennsylvania	14%	11.0	24.7	13.7
Michigan	19%	9.5	22.0	12.4
Massachusetts	31%	1.4	11.4	10.0
New Jersey	23%	6.9	16.5	9.5
Florida	4%	0.6	8.7	8.2

Electrification will slash greenhouse gas emissions

The NREL study shows that, relative to a business-as-usual scenario, electrifying the vast majority of residential and commercial buildings by 2050 could avert more than 306 million metric tons of CO_2 emissions.[111] This includes emissions resulting from the increase in electricity generation required to power the buildings. For reference, the U.S. residential and commercial sectors emitted 590 million metric tons of CO_2 equivalent from fuel combustion in 2018.[112] Electrifying homes and businesses, therefore, can cut building emissions by roughly half of today's emission levels.

The emission reductions would be even greater if the U.S. were to power its electricity grid with 100% renewable energy sources like the sun and the wind. Meeting the nation's current technical potential for electrifying buildings would cut direct carbon dioxide emissions — the emissions created by burning fossil fuels in buildings — by 416 million metric tons of CO_2, representing 71% of all emissions from buildings in 2018.[113] Powering the grid with 100% renewable energy would mean that the nation could realize all of those emission reductions without increasing emissions from fossil fuel power plants.

The states with the largest potential for reducing carbon dioxide emissions are, predictably, some of the most populous states — namely California, Texas and New York. However, likely because of the current lack of electrification, continued reliance on fossil fuels in buildings in the Northeast, and high seasonal heating demand, New York has the highest potential emissions reductions, as is shown in Table 1.

Electrification will slash gas usage and save energy overall

Gas is the main fossil fuel used in our homes and businesses, and a major source of the greenhouse gas emissions and air pollution that result from direct fuel use in the residential and commercial sectors.

Electrifying buildings would help slash our dependence on gas. An analysis of NREL's *Electrification Futures Study* data showed that electrifying most of the nation's buildings could reduce our consumption of gas by more than 7 trillion cubic feet in 2050 relative to the reference scenario.[115] Similarly, electrification of buildings could reduce consumption of diesel fuel by 1.1 billion gallons and reduce consumption of liquefied petroleum gas by more than 5 billion gallons in 2050 relative to the reference scenario.[116]

Switching to electricity to power our homes and businesses would also allow us to power them more efficiently. The same analysis of NREL data showed that relative to a business-as-usual scenario, electrifying most of our buildings by 2050 would mean that they would use 30% less total site energy in 2050.[117]

The states that stand to gain the most in terms of reduction of gas consumption and overall site energy usage are mostly in the Northeast and Midwest, as well as California. As previously discussed, this is likely because buildings in the southern U.S. are more likely to be all-electric already and have lower seasonal heating demand.

The residential sector represents the largest opportunity for benefits of building electrification, with almost 68% of the countrywide savings in gas usage, and almost 71% of the total energy use savings.[119]

TABLE 2: TOP 10 STATES FOR POTENTIAL REDUCTION IN GAS USAGE IN ELECTRIFICATION SCENARIO[118]

State	Reduction in total pipeline gas usage (billion cubic feet)	Reduction in total site energy usage (trillion Btu)
New York	652.1	566.9
California	608.6	513.2
Illinois	460.1	396.5
Pennsylvania	410.8	350.0
Ohio	404.1	348.8
Texas	378.4	368.0
Michigan	376.6	320.4
New Jersey	266.4	235.1
Wisconsin	244.7	199.4
Indiana	220.1	190.8

Electrification leads to a modest increase in electricity consumption

Because so many end-uses that currently rely heavily on fossil fuels would be electrified in the transition to electric buildings, the demand for electricity will increase. In particular, analysis of the NREL data found a nationwide increase of about 429 terawatt-hours (TWh) of electricity usage in 2050 under the electrification technical potential scenario.[120] This is equivalent to 11% of the nation's total 2019 electricity consumption.[121]

In some places, peak electricity consumption will shift from summertime to wintertime because of the energy demand of heating.[123] Adopting energy efficient appliances and weatherizing homes can reduce electricity consumption during these peak periods, while distributed generation and energy storage can decentralize electricity supply, all of which helps limit any impact on the grid.

TABLE 3: TOP 10 STATES FOR 2050 ELECTRICITY USAGE INCREASE IN ELECTRIFICATION SCENARIO[122]

State	Increase in total electricity usage (TWh)
New York	50.1
California	38.9
Illinois	31.3
Pennsylvania	31.2
Ohio	27.3
Michigan	27.0
Wisconsin	20.0
New Jersey	19.7
Indiana	14.7
Massachusetts	14.4

Electric technologies can repower America's buildings

Electric space and water heating systems are more widely available and more affordable than ever before. In warmer climates, electric systems have lower operating costs, and thus have been more widely adopted, but improvements in these technologies have made them viable even in colder regions like the Midwest and the Northeast.[124]

Heat pumps

Heat pumps are among the most widely installed electric-powered space and water heating systems and have high potential for more widespread installation due to recent improvements in efficiency in colder climates.[125]

Heat pumps pull heat from outside the system and move the heat into the building as desired. Heat pumps use the same technology — the vapor compression cycle — as refrigerators and can operate in both directions: heating in the winter and cooling in the summer.[126]

Heat pumps fall into two categories: air-source heat pumps and ground-source, or geothermal, heat pumps. Air-source heat pumps pull heat from one air mass and transfer it to another — heating by moving energy into the building and cooling by moving it out.[127] Geothermal heat pumps use the earth's relatively stable, year-round temperature from underground, but otherwise work similarly to air-source heat pumps.[128] Installation of geothermal heat pumps is more costly than air-source heat pumps, as piping must be installed underground, but they offer significantly higher efficiency and potentially lower long-term energy costs.[129] Geothermal systems can also capture waste heat to use for water heating, further reducing emissions and costs.[130]

Heat pumps are much more efficient than burning fossil fuels for heat. The coefficient of performance (COP), or the number of units of heat produced per unit of energy input, for air-source heat pumps ranges between 3.2 and 4.5, while geothermal heat pumps can reach COPs of 3.0 to 6.0.[131] By comparison, electric resistance heating has a COP of 1.0.[132] Modern high-efficiency gas furnaces have COPs just under one.[133] Older fossil fuel furnaces are often even less efficient, and can lose up to 40% of the heat they produce.[134]

Two 36-ton geothermal heat pumps at the College of Southern Idaho, Twin Falls, Idaho. Photo credit: Bruce Green/NREL

The outside unit of an air-source heat pump. Photo credit: Ppntori via Wikimedia, CC-BY-1.0

While for many years air-source heat pumps could only work well in warmer, temperate climates, recent technological advances have made them functional in nearly every climate zone in the United States.[135] A Northeast Energy Efficiency Partnerships study found that modern air source heat pumps can perform well in cold climates, with some models able to operate in temperatures as low as -15 degrees Fahrenheit.[136]

Water heating

The two most common electric water heating technologies are electric resistance water heaters and heat pump water heaters. Electric resistance water heaters consist of a tank with submerged electric heating elements. These heaters usually last longer than the tanks of fossil fuel-fired heaters.[137]

Heat pump water heaters are tanks with heat pumps attached, which bring in heat from the air surrounding the tank and use that energy to heat the water. Heat pump water heaters also expel cool air, and thus can also act as an air conditioner if desired.[138] Research has shown that heat pump water heaters are a very efficient way to provide water heating. [139] A Natural Resources Defense Council study found that heat pump hot water heaters had COPs ranging from 2.8 in cold climates to almost 3.5 in warmer ones, meaning that for every unit of energy put in, they provided around three times as many units of heat.[140]

Although heat pump water heaters can be nearly four times the cost of conventional water heaters, they last longer and are much more efficient. In the long term, heat pump water heaters usually save consumers money despite the large upfront investment.[141]

Other, less common options for electric water heating include thermal exchange water and space heating (which uses heat from wastewater), carbon dioxide-based heat pump water heaters, single-unit outdoor heat pumps, and tankless electric units.[142]

Heat pump components in an integrated heat pump water heater. Photo credit: Kate Hudon / NREL

Electric appliances

Fossil fuel-powered appliances like stoves and dryers account for only a small share of building energy use but will be important to include in the transition to an economy powered by 100% renewable energy.

Induction cooking, for example, is a reliable alternative to cooking with gas. An induction burner utilizes electromagnetic coils to generate a fluctuating electromagnetic field, which induces smaller electric currents in the metal of an iron or stainless-steel pot that is placed on the stovetop. Since iron does not conduct electricity well, thermal energy is generated in the pan as the electric currents run through the metal.[143] Induction cooking is also a very safe method of cooking, as burners left on accidentally won't get hot, since a pan must be on the burner in order for heat to be generated. Temperature control is often a concern when moving away from gas stovetops, but according to Consumer Reports, induction stovetops are actually superior to gas in this regard.[144] Cooking times are also shorter, since heat is transferred directly into the pan. Induction cooking even improves air quality in homes, as gas stoves can emit excess combustion gases.[145]

Clothes dryers are another class of common appliance that often run on fossil fuel. Electric replacement options include standard electric dryers and heat pump dryers, both of which are much more efficient than fossil fuel-powered devices and, in the case of heat pump dryers, don't even require a vent outside the building.[146]

Additionally, pool heaters and hot tub heaters are sometimes powered by fossil fuels, so efforts to further electrify these technologies will assist in the complete electrification of the building sector.[147]

An induction stovetop. Photo credit: Dennis Schroeder/NREL

A Miele heat pump clothes dryer. Photo credit: Suzyj via Wikimedia, CC BY-1.0

A solar water heater. Photo credit: RanjithSiji via Wikimedia Commons. CC BY-SA 3.0

Solar thermal systems

While technically not an electric system, solar thermal systems represent another way to provide space and water heating without the use of fossil fuels. Solar thermal technologies provide space and water heating by capturing and storing the heat of the sun. To provide space heating, the sun's energy is first captured in solar collectors. Heat is then transferred from the solar collector to the air and distributed through buildings using fans. To provide water heating, thermal energy is captured in solar collectors and transferred to the water through insulated piping, which then fills a hot water tank.[148] Solar thermal and hot water systems come with backup systems, which can be electric.[149] Solar thermal energy has been used for decades and can provide clean space and water heating.[150]

District energy systems

For commercial buildings that are physically close together, such as on a campus, it is often more efficient to address the heating and cooling systems as a unit. District energy systems supply energy to buildings through a communal plant that provides heating, cooling and sometimes electricity.[151] By aggregating the energy needs of several buildings, district energy systems allow for greater energy efficiency and the potential to utilize more renewable energy resources.[152]

The primary benefit of district energy systems is efficiency. Just as with heat pumps, district energy systems can achieve incredibly high COP ratings.[153] For instance, Stanford University reports that its district energy system achieves a combined annual COP of 6.3.[154]

While district energy systems are still relatively uncommon in the United States, as of 2019 the International District Energy Association reports nearly 1 billion square feet of commercial space using a district energy service in North America.[155] They are more common in Europe and are especially useful in densely populated areas.[156]

Generally, district energy systems are powered by fossil fuels.[157] However, in recent years there has been more interest in running these systems with renewable energy. Geothermal heating, solar thermal, solar PV and wind energy all have the potential to power district energy systems and help electrify the commercial building sector with clean, renewable energy.[158]

A plate heat exchanger connecting the heating system of the Elks Rehabilitation Hospital in Boise, Idaho to the city's geothermal district heating system. Photo credit: Bruce Green/NREL

Adopting efficiency and other technologies can maximize the benefits of electrification

Building electrification can aid the transition to an energy system powered completely by renewable sources. Through a variety of means, such as improved energy efficiency in our buildings and the use of energy storage in our homes and offices, we can more quickly transition to an economy powered by 100% renewable energy.

These technologies will become increasingly important as electrification increases demand on the electric grid. According to NREL estimates, meeting the technical potential for electrification of all sectors of the economy could push electricity consumption as high as 8,000 terawatt-hours by 2050, just over a 100% increase above 2019 consumption.[159] This increased demand will be a challenge for utilities and policymakers, but the technologies discussed below can help relieve the burden on the grid by reducing demand, allowing flexibility in generation, and producing electricity on-site.

Energy efficiency

Improving the energy efficiency of our buildings will be paramount in addressing any increased strain on the grid resulting from the electrification of homes and businesses. Reducing energy demand will also make the job of switching from fossil fuel-powered sources of electricity to renewable sources much easier.

Improvements in energy efficiency can be large-scale investments, such as improvements to home insulation and the installation of energy-efficient windows, or they can be smaller, such as switching out inefficient light bulbs and using smart plugs to power down appliances when not in use.

Widespread improvements in the energy efficiency of our buildings have the potential to reduce emissions and curb demand on the grid. A New York City plan to improve the energy efficiency of its buildings includes requirements for businesses and companies to repair broken or ineffective heating distribution and ventilation systems and incentives to install more efficient lighting.[160] The city's full plan is estimated to reduce greenhouse gas emissions by 2.7 million metric tons by 2050, which has a similar impact to taking around 560,000 cars off the road.[161]

High-efficiency appliances such as washing machines, dryers and refrigerators can also reduce a home's electricity demand.[162] Appliances are the third-largest source of energy use in a home, after space heating and water heating, accounting for nearly a tenth of home energy consumption.[163] Efficiency improvements for large appliances therefore represent an important step in reducing residential energy consumption.

Beyond larger-scale improvements, home and building owners can also focus on smaller steps, such as upgrading to energy-efficient appliances and lighting. Increasing the use of efficient bulbs like LEDs could greatly reduce unnecessary energy usage. LED bulbs can use up to 80% less energy than traditional incandescent light bulbs and last about 25 times longer, saving consumers time, money and effort.[164] The U.S. Department of Energy estimates that widespread adoption of LED lighting could eventually save enough energy to equal the average yearly output of 44 large electric power plants, equaling monetary savings of $30 billion.[165]

Energy storage

Energy storage technologies can play a critical role in managing supply and demand for electricity — reducing strain on the grid and giving consumers the added ability to reap the benefits of on-site renewable energy systems and off-peak electricity rates. This can lower costs for consumers and give them more flexibility in the ways they use clean, renewable electricity.

Energy storage systems — such as batteries located "behind the meter" in a consumer's home — allow consumers to buy or generate electric power when it is cheaper or more readily available, and then use that energy whenever it is needed. Energy storage is especially critical in buildings that generate electricity using solar panels, as it enables buildings to continue to use locally generated renewable electricity even after the sun goes down.

Behind-the-meter energy storage capacity, often in the form of batteries, grew substantially in 2018, surpassing front-of-meter storage capacity (such as industrial batteries and pumped storage) for the first time.[166] In addition to the potential for cost savings and emission reductions, battery storage can serve as a valuable backup source of energy during a blackout.[167] Looking forward, traditional lithium-ion batteries are being combined with cutting-edge zinc-air storage technologies to make battery storage even more efficient and cost-effective for consumers.[168]

The rapid adoption of electric vehicles (EVs) also presents a new opportunity to store electricity and provide it to the grid as needed. While the widespread electrification of the transportation sector will increase demand on the grid, the batteries within EVs have the potential to become an important energy storage resource using bi-directional power flow.[169] In times of high demand, EV batteries could discharge electricity to the grid, eliminating the need for increased generation.[170] Combined with the development of smart, integrated electric grids, the batteries in electric vehicles could be used to provide power to the grid at times of peak demand and serve as a source of backup power in an emergency.[171]

Another cost-effective behind-the-meter energy storage option is the grid-interactive electric water heater. Pre-heating water when electricity costs are low and renewable energy is plentiful allows energy to be stored as heat, and a highly insulated and efficient tank can help avoid resulting energy losses.[172]

"Behind-the-meter" battery storage at an apartment complex in Los Angeles County, California. Photo credit: Clean Energy Group via Flickr, CC-BY-NC-ND 2.0

Energy management technologies

Energy management tools utilize real-time information, communications and control technologies to shift the bulk of a consumer's electricity use to times when electricity prices are lower or renewable energy is more widely available. These technologies can save consumers money but can also be used to reduce peak impacts on the grid and allow greater flexibility to accommodate the increased demand that will come from widespread building electrification.[173]

Currently, one of the most common energy management technologies is the demand-response thermostat, which automatically adjusts to specific temperatures in order to better handle fluctuations in grid-wide electricity demand.[174] In return for turning down their thermostats during times of high demand, consumers receive a smaller electricity bill and often a rebate from the utility company.[175] Energy management technology, which includes demand flexibility, is also being utilized for water heating, electric vehicle charging and other appliances. One study from Rocky Mountain Institute found that by using demand flexibility, residential customers can already reduce their electricity bills by 10%-40%.[176]

Distributed renewable energy technologies

Distributed renewable energy technologies like rooftop solar panels can help spur electrification by allowing more of a building's energy load to be met by affordable, clean energy. They can also help utilities better adjust to increased electricity demand resulting from building electrification, as much of the additional demand will be met on-site.

Distributed solar panels can help smooth the process of electrification, both for the consumer and policymakers. When a building becomes fully electric, there is often increased demand on the electricity grid — which may require utilities to make extra investments in distribution management, transmission and power generation infrastructure.[177] The installation of local solar panels can help mitigate the increased demand on the grid by supplying the majority of a home's electricity on-site.[178] The production of renewable energy on-site can also help bring down electricity bills for consumers as they transition to electric systems.[179]

Full electrification and the installation of solar PV systems are two important components of zero net energy (ZNE) buildings — buildings that produce at least as much clean, renewable energy as they consume. ZNE buildings are ultra-efficient, using innovative technologies like insulation and energy-efficient lighting and appliances to slash overall energy consumption, and generate electricity through clean and renewable sources, usually via rooftop solar panels. ZNE buildings are becoming increasingly cost-effective and are poised to make up a greater share of new homes in the coming decades.[180]

Zero net carbon vs. zero net energy buildings: What's the difference?

Zero net energy (ZNE) homes and buildings produce as much renewable energy on-site as the building uses in a year, thus having a "net" zero impact.[181] The production usually comes from rooftop solar panels, and energy usage is cut through extensive efficiency improvements.[182]

Zero net carbon (ZNC) or zero emission buildings are those that are highly efficient and receive all their energy from carbon-free sources.[183] Unlike ZNE buildings, ZNC buildings may draw electricity from the grid in excess of what they produce on-site, but that electricity comes from zero-carbon sources such as renewable energy.[184]

Building electrification often makes sense for consumers

Advances in technology have made electric systems in homes and commercial buildings more affordable, effective and efficient. The installation of fully electric systems in homes and buildings now makes sense for owners in almost all instances of new construction, and even makes retrofitting an appealing option in some scenarios.[185]

Lower lifetime costs for new construction

Rocky Mountain Institute (RMI) found that across the country, electrification is the most cost-effective option for consumers building a new home.[186] Their study, *The New Economics of Electrifying Buildings*, examined the costs of incorporating electric technologies in buildings in seven cities (Austin, Texas; Boston; Columbus, Ohio; Denver; New York City; Minneapolis; and Seattle) and found that in every city, installing electric technologies in new construction saved consumers money over installing gas or oil systems.[187]

RMI found that in every city studied, heat pump installation reduced lifetime costs for consumers in new construction compared to similar new construction using gas, propane or heating oil infrastructure. In these new construction scenarios, consumers opting for heat pump installation over fossil fuel heating methods could save between $1,600 and $6,800 in net-present cost for space and water heating over a 15-year period, though in other cities savings could reach as high as $13,700.[188]

Retrofitting from expensive fossil fuels

While retrofitting buildings to run on electric systems is almost always more expensive than installing them during new construction, there are some scenarios when retrofitting already makes financial sense for consumers.[189] Nearly 10% of the nation heats their homes primarily using heating oil or propane, two of the dirtiest and most expensive fossil fuels.[190] By switching to an electric heat pump, homeowners who use heating oil or propane can realize thousands of dollars of savings and cut the greenhouse gas emissions of their heating system by 40%-50%.[191]

Switching from existing gas heating systems to electricity is currently not cost-effective in many parts of the country.[192] Studies from both the U.S. Department of Energy and Rocky Mountain Institute have found that replacing a gas furnace with an electric heat pump is usually only financially beneficial when both the furnace and A/C unit are at the end of their useful lives.[193] But even in these cases, the high upfront costs of retrofitting may not be recouped for years. Rocky Mountain Institute's study found that in both Chicago and Providence, RI, consumers lost money over a 15-year time period if they retrofitted with heat pumps instead of gas.[194]

Figure 6 compares the 15-year savings of retrofitting a home with an electric heat pump versus a new gas system with or without an A/C unit in four cities. In

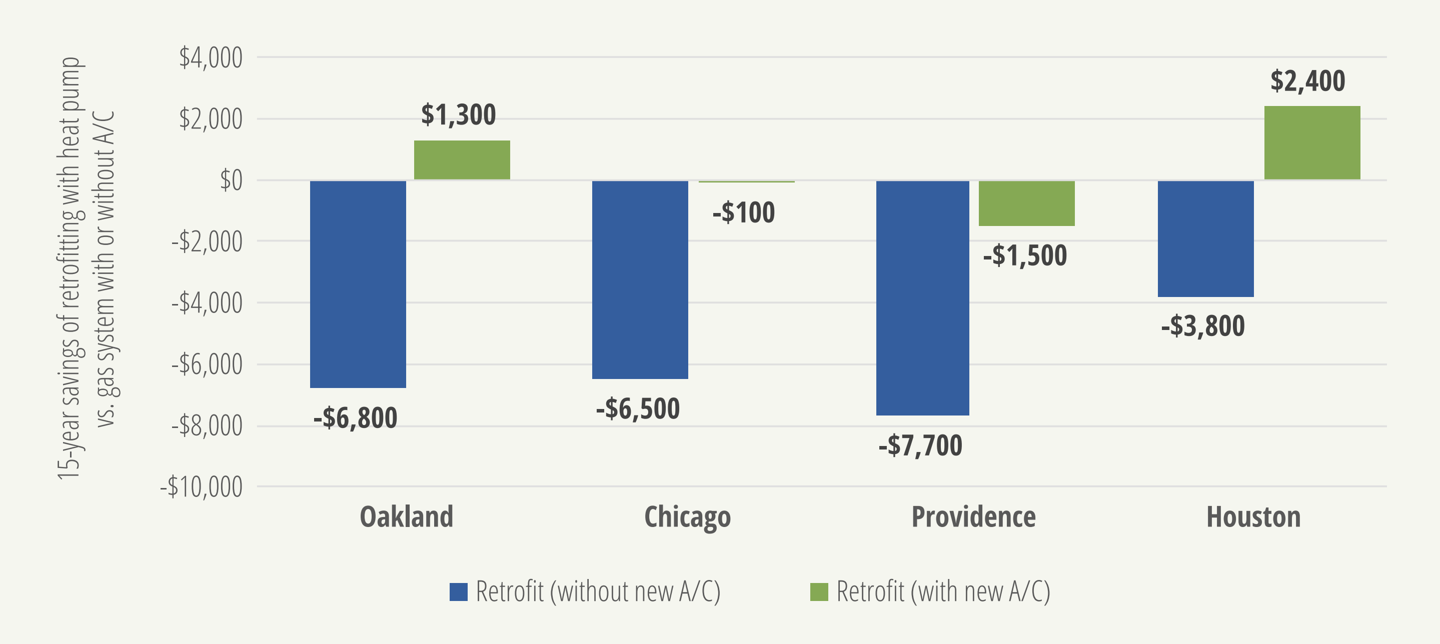

Figure 6: Savings from retrofitting with electricity for space and water heating compared to gas[195]

Oakland and Houston, electric heat pumps save owners more than a thousand dollars over new gas systems and air conditioners, while in Chicago the difference is nearly zero and in Providence it still costs more over 15 years to install a heat pump than a gas system and A/C. In all cases, a new gas system without a new A/C unit has a lower lifetime cost than a new electric heat pump.

However, with a typical lifespan of 30 years for gas furnaces, continuing to replace failing gas heating systems with new fossil fuel-burning systems either guarantees that they will still be operating long after the time by which the United States must end fossil fuel use to protect the global climate or be retired before the end of their useful lives. For these reasons, it makes sense for the public sector to encourage the replacement of existing gas heating systems with electric systems, despite the current cost differential.

Affordable, clean electricity from solar panels

Fully electrified homes can better utilize the clean electricity that comes from rooftop solar panels. With complete electrification, there are more electric appliances to power and less electricity needs to be put back onto the grid. In states with pro-solar policies, homeowners with solar energy can save between $10,000 to $30,000 over a 20-year period.[196] Building electrification is even more crucial to making solar installations financially viable in areas without net metering and other beneficial solar policies, as consumers are not adequately compensated if their excess clean electricity flows onto the grid.

Combining solar panels with batteries and demand flexibility technologies, such as smart preheating of building spaces and hot water, can help a solar PV system meet even more of a house's electricity demand.[197] All-electric homes can fulfill much or all of their energy needs with rooftop solar panels — benefiting homeowners financially and helping to transition to a 100% clean, renewable energy system. Solar energy with storage is also a useful and important tool for disaster resilience, continuing to power homes even when the grid is down without the dangers associated with a fossil fuel backup generator.[198]

Common barriers hinder building electrification

While electrification has become an increasingly appealing option, there are still some barriers that stand in the way of widespread adoption. In order to fully electrify the building sector, policymakers, contractors and owners will have to address these issues.

Lack of consumer and contractor familiarity with electric technologies

The technology needed to completely electrify our buildings is widely available and is often cost-competitive with fossil fuel-powered technologies — especially in new construction — and yet adoption of these electric technologies is not as common as it should be. Lack of familiarity with these electric technologies, from both consumers and contractors, is one reason why building electrification is not widespread.[199]

Consumers may not be aware of improved technologies for electric heating and cooking — such as advanced heat pumps and induction cooktops — that overcome the limitations of previous generations of electric appliances.[200] Negative experiences with early heat pump systems in the 1970s or 1980s, or difficulties with older electric stoves, may make some consumers reticent to adopt modern versions of those technologies that are often superior to their fossil fuel-powered counterparts. For example, Consumer Reports finds that induction stovetops are more controllable and faster to reach a given temperature than gas stoves.[201] Gas stoves and heating systems can also make indoor air quality unsafe, are a source of major outdoor air pollution, and require infrastructure that is responsible for thousands of injuries and deaths in the last 20 years.[202]

Lack of familiarity with the technology is not just a barrier for consumers, but also for the contractors tasked to recommend and install new technologies in homes and buildings.[203] A lack of knowledge can often impede contractors from recommending the new electric technologies, as they may not be familiar with recent advancements in these technologies and may feel uncomfortable installing them.[204] If the contractor is unfamiliar with electric technologies, projects may become more expensive due to longer timeframes or mistakes made during the process.[205]

Higher capital costs of retrofitting

High upfront capital costs are sometimes a barrier to retrofitting buildings to run on electricity.[206] These costs can deter customers from electrifying their buildings.

While prices for electric heating systems and installation vary across the country, on average in the U.S. ductless air source heat pump systems cost between $4,000 to $5,000 including installation, and central air heat pump systems average $5,600.[207] Additionally, buildings may need an upgrade in electricity service in order to power newly electric systems. This is often another expensive upfront investment and could possibly deter consumers from choosing to retrofit their homes.[208] To upgrade electricity service in preparation for electrified space heating, one company estimated a cost of $4,700 for a single-family home, $5,800 for a small to medium office and $35,000 for a low-rise apartment building.[209]

Addressing high capital costs requires a range of approaches. One approach is to prioritize replacement of heating and A/C systems that are nearing the end of their useful lives and that would require a capital outlay to replace anyway. Retrofitting with electric systems at the end of a fossil fuel system's life can reduce the incremental cost of the retrofit as experienced by the consumer. One study by NREL found that retrofitting with heat pumps when an A/C unit is at the end of its useful life is cost-effective in most cases when the furnace runs off oil or propane. When both the furnace and A/C unit are worn out, electrification retrofits are cost-effective in nearly all cases for oil and propane and over half of homes that run on gas.[210] Providing financial incentives for retrofits or low-cost financing to spread the cost over time may be necessary to encourage consumers to commit to the high upfront investments needed for electrification.

Long lifetime of fossil fuel systems leads to low turnover

Systems and appliances like gas furnaces and stoves have long lifetimes, often lasting decades.[211] This means owners are locked into long periods of fossil fuel use, in which the machine is emitting greenhouse gases and harming air quality, and often becoming less efficient over time.[212] And since retrofits with electric equipment can be expensive, long lifetimes for fossil fuel systems means there are fewer points at which is economically efficient to replace them — often only at the end of their useful life.[213]

Increased demand on the electric grid

Beyond personal barriers for consumers and contractors, there are also systems-level challenges that policymakers will have to address. These include the effects of increased electricity demand on the grid.

Accommodating the increased electricity demand from building electrification does present its own set of challenges.[214] Studies show that while electrifying a handful of buildings will have minimal impact on the grid, widespread building electrification could significantly increase electricity demand.[215] NREL projects that, in the electrification technical potential scenario, electrification of the residential, commercial, transportation and industrial sectors could push electricity consumption as high as 8,000 terawatt-hours by 2050.[216] Electricity consumption patterns and the timing of peak demand may also shift dramatically.[217]

While changes in the scale and timing of electricity demand have the potential to strain the grid, forward-thinking policies from utilities and governments can minimize this risk. For example, proactively upgrading distribution and transmission systems in strategic locations can help accommodate increased demand in both the short- and long-term.[218] These upgrades will eventually be necessary for widespread electrification in both the buildings and transportation sectors.[219] One study found that $230 billion to $690 billion worth of investments in transmission infrastructure will be needed by 2050 to accommodate increased electricity demand.[220] However, the further adoption of demand-response technologies, battery storage and on-site renewable energy resources can sometimes help offset or defer these costs, while also adding flexibility to the electricity grid, allowing it to better absorb additional demand.

Regulatory barriers

Policies that prevent incentives for electrification or reduce the benefits of electrification make it less appealing or even impossible for Americans to transition away from fossil fuels. Some states have legacy restrictions on fuel switching that prevent incentivizing electrification in favor of installing gas systems, making installing electric systems more expensive than it could be.[221] This forces residents to pay the full cost of electric systems up front or resort to installing gas systems that are more efficient than the old ones but still fossil fuel-powered, and is antithetical to eliminating emissions by mid-century, a necessity to avoid the worst impacts of global warming. Changing these policies to encourage switching to electric technologies and to discourage or disallow installing new fossil fuel-powered systems can help spur the needed country-wide electrification.

Another regulatory barrier to electrification is the existing utility rate designs that do not incentivize demand response or load flexibility. These prevent customers who electrify from maximizing the benefits of that switch.[222] Changing regulations to mandate that utilities implement dynamic rates like time-of-use rates or use demand response and flexibility tools to reduce overall energy use and costs can help customers benefit more from electrification.

Costs of incentives and policy reforms

Fully electrifying buildings by mid-century will require strong and consistent public policy support, including mandates, subsidies and assistance with financing. The expenditure of resources for these programs could be seen by some as competing with other critical clean energy investments, such as investments in renewable energy, building energy efficiency, clean vehicles and more.

Currently, many energy efficiency incentive programs do little to support electrification — often offering generous incentives to upgrade an inefficient gas heating system to an efficient one, but less incentive to switch to an electric system.[223] Some efficiency programs even prevent customers from fuel switching if they want rebates from a utility. In Minnesota, for instance, the Conservation Improvement Program does not allow utilities to offer incentives to switch from a gas furnace to an electric heat pump.[224]

Some states have begun to adjust their approach, establishing generous incentives for owners to convert to electricity from dirtier fossil fuels.[225] Massachusetts, for instance, now gives rebates of up to $7,200 to building owners that switch to electric heat pumps from heating oil.[226]

In order to repower our economy with clean electricity by mid-century, policymakers will need to adjust the mission and operation of existing energy efficiency programs. They need to ensure that those programs have access to sufficient resources without depriving other critical clean energy programs of resources or attention.

Policy recommendations

Electrifying our nation's buildings will be necessary if America is to embrace a future of 100% clean, renewable energy.

The technologies needed to electrify our buildings are rapidly improving and costs are falling. Still, there are significant financial and institutional barriers to adopting electric systems in buildings. **To help overcome these barriers and ease the transition to electrification, policymakers on the local, state and federal levels must:**

Adopt building codes that incentivize or require electric systems in new construction

Constructing new buildings with fully electric systems is already cost-effective. Recognizing the benefits for consumers and urgency to begin the transition to complete building electrification, several cities, including San Jose, Berkeley, Oakland and San Francisco, California, as well as Seattle, have proposed or adopted building codes to ban new gas infrastructure.[227] Some states, including New York, Colorado and California, are considering banning or discouraging new gas installations statewide.[228]

Building codes are local or state ordinances that mandate certain standards for building construction.[229] Including stricter efficiency standards and electrification incentives within the code can help drive the construction of greener buildings. Municipalities and states that want to experiment with more aggressive building codes can begin by adopting "stretch" codes that enable contractors to become familiar with new technologies before they become mandated.[230] Stretch (or "reach") codes are stronger, more aggressive buildings codes than a base code, which cities can adopt voluntarily — often receiving incentives to do so — in order to ensure buildings are more energy efficient.[231]

Progress is not restricted to individual municipalities or states, however. In 2019, government representatives from across the U.S. voted to update the International Energy Conservation Code (IECC) to make building codes for new buildings more efficient.[232] The IECC is used as the basis for building codes in most states, so the update should improve efficiency significantly across the country, although several industry challenges to the update have resulted in higher costs for consumers and less efficient new buildings than originally proposed.[233]

Building codes can also be used to incentivize, and eventually require, the construction of zero net energy (ZNE) or zero net carbon (ZNC) buildings.[234] Many states and local jurisdictions already have aspects of ZNE and ZNC buildings as part of their codes.[235] In California, for example, most new single-family homes and some multi-family buildings must install a solar PV system.[236] The state also has strict energy efficiency standards for new buildings.[237] Eventually, states and cities can utilize these codes to require that all new construction conform with ZNE and ZNC standards.[238] The updated 2021 IECC codes also included ZNC codes that local governments can choose to adopt.[239]

Building codes that mandate new construction be all-electric or ZNC/ZNE could help start the transition to clean buildings and are especially important given the long lifetimes of buildings and building systems. If new buildings are built with fossil fuel-powered systems in place, they will likely last through 2050, by which time the U.S. needs to have cut all emissions that contribute to global warming. The power to adopt building codes varies by state, with adoption a local responsibility in some places and a state responsibility in others. Both local and state governments have important roles in adopting and enforcing strong building codes.

Finally, policymakers should use building codes and utility regulation to encourage the installation and use of technologies and practices that promote the flexibility and resilience of the electric grid. These include distributed generation technologies such as solar panels, energy storage technologies, and smart electric systems in buildings that can regulate demand according to price signals or in response to electricity supplier signals. It is also important that utilities and electricity suppliers be able to signal buildings to change demand when necessary.[240]

Implement rebate programs, incentives and low-cost financing

While a fully electric building usually costs less to power than a building using gas or oil over a period of several years, the upfront cost for a retrofit can be higher. To incentivize the transition to electric infrastructure, government programs should be established that offer rebates, incentives and low-interest loans to homeowners, contractors and builders who want to install electric systems and appliances.

Massachusetts recently rolled out a new energy efficiency plan that includes rebates and incentives for building electrification. The policy's goal is to improve efficiency, ultimately saving consumers money on energy bills and lowering greenhouse gas emissions. It is estimated that the three-year plan will deliver over $8 billion in customer benefits.[241] Previous policies allotted rebates of $1,200 for consumers who wanted to install a heat pump, while the new program offers rebates of up to $7,200 for oil customers looking to electrify and switch to a heat pump.[242] Through this policy, consumers currently using the dirtiest and most inefficient fuels will have the largest incentives to electrify.

These programs can also be applied midstream in the supply chain — to distributors or contractors — in order to simplify logistics, a tactic that has proved successful in existing programs in Vermont and New York.[243] This allows consumers to pay a lower up-front cost at the point of sale, simplifies logistics, reduces marketing costs, and encourages distributors to have a greater supply on hand.[244]

Policymakers should also implement other non-traditional financing mechanisms like tariffed on-bill financing. Tariffed on-bill financing allows a utility to pay for the cost of efficiency or electrification upgrades for a consumer and then collect their investment back on the customer's bills in fixed payments over time.[245] This removes the cost barriers to electrification, provides utilities with a reliable source of income, and solves the logistical problem of electrifying rental properties.[246]

Finally, policymakers should implement broader rebate and incentive reform. Specifically, they should end rebates for fossil fuel-powered systems — including gas-powered systems — and prioritize efficiency upgrades in general and especially for those buildings that cannot be electrified in the short term.[247]

Implement regulatory solutions, including rate design and fuel-switching regulation changes

Improved rate design, including time-of-use rates, critical peak pricing and other dynamic pricing models can help lower bills for electricity customers, especially those with devices that can schedule use based on overall demand or price.[248] These types of rates are already in place and saving consumers money in places like Houston and Oakland, California.[249]

Another important regulatory change is to allow fuel-switching incentives to cover electric devices. Currently, many states have programs that incentivize upgrading the efficiency of a gas-powered system or switching from a dirtier fuel to gas, but do not incentivize electrification and in some cases may even prohibit switching to electricity.[250] Allowing and incentivizing electrification is an important regulatory change that can be made to help reduce emissions and energy use while also making people safer.[251]

Create and expand tax incentives for electrified buildings

There are already a few tax incentives at the federal and state levels for buildings that are energy efficient and/or utilize electric technology.[252] Several states have implemented property tax exemptions that exclude any clean-energy upgrades that homeowners make — such as the installation of geothermal heat pumps — from the property value for tax purposes.[253] These exemptions can help eliminate disincentives for building owners to install new electrical systems.

Establishing a permanent tax break on the federal level would also help to encourage electrification. In the past there have been federal tax breaks for energy-efficient buildings, but their effectiveness has sometimes been undermined by haphazard implementation. For example, the Commercial Buildings Energy Efficiency Tax Deduction is a federal tax deduction that allowed commercial building owners to reduce their tax bills if buildings save at least 50% of the heating and cooling energy relative to minimum efficiency standards set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).[254] However, this tax deduction has always been temporary, being renewed every few years in a tax extension bill and often applied retroactively.[255] This reduces the incentive for architects and developers to incorporate energy efficiency upgrades or electric systems, as they don't know with certainty if their building will be eligible for a tax break. For these types of tax deductions to work effectively and incentivize energy-saving upgrades, they should be implemented on a more permanent basis.

When considering the implementation of tax incentives, policymakers should design them to be accessible to the broadest section of the public. For instance, making tax credits fully refundable would make it so that even taxpayers whose liability is below zero for a year could take advantage of tax incentives for efficient, electric technologies.[256] This could help encourage more widespread electrification of buildings and appeal to building owners who may not have been able to benefit from a non-refundable tax credit.

Require building energy transparency and implement building performance standards that limit carbon emissions

Mandatory reporting about the energy source and performance of buildings helps to ensure that any investments that owners make to improve efficiency and electrify are reflected in the building's value.

Cities including Berkeley, California; Austin, Texas; Edina, Minnesota; Orlando, Florida; and Pittsburgh have implemented programs to uncover energy savings opportunities in the city's buildings and give buyers information about the efficiency of buildings.[257] Berkeley's Building Energy Saving Ordinance (BESO) requires homeowners and commercial building owners to complete an energy efficiency assessment of their buildings, publicly report the results of the assessment, and disclose information about energy sources and performance to prospective buyers.[258] Tailored recommendations are provided to building owners by the assessors, giving them the opportunity to opt-in to energy incentive programs like Energy Upgrade California, which provides rebates for efficiency upgrades and connects consumers with licensed contractors.[259] Austin's ordinance is similar, and requires all commercial buildings to report their energy ratings on a yearly basis, and single-family homeowners to conduct an audit before sale.[260]

These programs also give people looking to buy a building more information about the energy performance of the building, enabling would-be buyers to factor it into their decision. Although some states, counties and cities have building energy disclosure laws, in most of the country disclosure of information on a building's energy use is not required, so when a homeowner chooses to electrify their systems and appliances, or make energy-saving upgrades to their home, the value of these projects is not reflected in the home price and the investment is effectively lost.[261] Conversely, knowing that efficiency upgrades could influence a future sale can incentivize these kinds of repairs. One study of Austin's program found that the city's law encouraged efficiency investments among homeowners and home buyers.[262] Homes that consume less energy, and thus save residents money, should be worth more and transparency initiatives can help shape the market to value efficiency and encourage electrification.

Building performance standards are an emerging tool to help decarbonize existing building stock. They function for existing buildings similarly to efficiency standards for new buildings.[263] Building performance standards set a benchmark for buildings on metrics like energy efficiency, fuel use and emissions, mandating that building owners undertake measures to meet the standard, and raising the benchmark over time to achieve continued improvement.[264] Where implemented, building performance standards have already successfully reduced emissions, such as in Boulder, Colorado, where the city saved 1.9 million kilowatt-hours of electricity and averted 3.9 billion metric tons of CO_2 in eight years.[265] Performance standards should be implemented alongside funding from local governments or utilities to help building owners meet the standards.

Educate developers, contractors, retailers and consumers about electrification

Information on electrification can be useful for consumers and contractors, as it can sometimes be difficult to understand the possible benefits and costs that result from switching to a new and unfamiliar technology. Government offices at the federal, state and local levels can help fill information gaps by posting materials online, launching public information campaigns and establishing programs that help owners identify which electric appliances and systems are right for their buildings, and which programs are available for owners and tenants to support electrification.

In an effort to reduce greenhouse gas emissions, the city of Boulder, Colorado, has created programs to promote building electrification and make installation of electric technologies like heat pumps easier and more affordable for building owners. The city has developed a system that provides single-family homeowners with a detailed assessment of their energy usage and a personalized plan for transitioning to home electrification. These assessments contain various options for electrification of space and water heating, improvements in energy efficiency, electric vehicle acquisition, and installation of on-site solar energy. The city also partnered with Mitsubishi Electric, one of the world's largest producers of high-efficiency heat pumps, to launch a campaign focused on promoting heat pump installation. This public information campaign has been largely successful; Boulder witnessed a three-fold increase in heat pump installations in the first year and is now trying to make the program more accessible to more residents.[266]

Contractors and builders can also benefit from information and education when it comes to new electric technologies.

Government-funded and -run training programs and seminars could help increase awareness of electric technologies amongst contractors, as well as help improve the quality of their installations and maintenance.[267] Running similar programs for developers would boost awareness of current electric technologies and encourage electrification of new developments. Encouraging retailers to carry electric systems and appliances and providing them information and materials they can use to educate customers can help raise awareness and change purchasing patterns.

Update appliance efficiency standards

Efficiency standards for appliances and lighting are set at both the state and national level and are updated with some regularity.[268] These standards help precipitate broad, if incremental, changes in efficiency with meaningful savings in energy usage and emissions. While highly efficient devices and appliances are already being bought and used across the country, updated standards with strong efficiency mandates would raise the baseline efficiency level across the board, decrease energy use nationwide and spur development of even more efficient products.

Methodology

Estimates of greenhouse gas emission reductions and energy savings from building electrification are derived from data produced for the National Renewable Energy Laboratory's (NREL) *Electrification Futures Study*. This report examines estimates of energy use in 2050 in several scenarios, including a reference scenario and an electrification technical potential scenario, which formed the basis of this analysis. Detailed state-by-state data were obtained from the NREL, *Electrification Futures Study Technology Data*, accessed 2 October 2019 and available at https://data.nrel.gov/submissions/92.

As part of the analysis, this report calculated the change in usage of various fuels between the two scenarios, including changes in diesel fuel, pipeline gas, kerosene, wood, and liquefied petroleum gas (LPG fuel, also known as propane) use, as well as the change in electricity use total site energy consumption and carbon dioxide emissions.

The NREL data is organized by scenario, year, technology used, state, sector, subsector, fuel used, and amount of energy used. All analysis was done using Python 3 in Jupyter Lab. To run the analyses, a subset of the data was created with only the two scenarios (Reference Electrification – Moderate Technology Advancement and Electrification Technical Potential – Moderate Technology Advancement), only data for the year 2050, and only data for the residential and commercial sectors.

Usage of diesel, gas, electricity and LPG fuel was converted from millions of British thermal units (as provided by NREL) into commonly used units. For diesel, gas and site electricity, the conversion factors provided by the Energy Information Administration (EIA) in *Units and Calculators Explained* were used (https://www.eia.gov/energyexplained/units-and-calculators/, accessed 13 November 2020). For LPG fuel, the conversion factors provided by the Energy Information Administration in the *Annual Energy Outlook 2016, Appendix G, Conversion Factors, Table G1* were used (https://www.eia.gov/outlooks/aeo/pdf/appg.pdf, accessed 13 November 2020).

To calculate total energy change between the reference scenario and the electrification technical potential scenario, energy usage for diesel, gas, LPG, kerosene, wood and electricity were summed for all end uses for each state in each scenario to arrive at total site energy use. Coal, steam and solar were excluded from the analysis because solar (for water heating) is not used in the residential and commercial sector in the NREL projections, and coal and steam are both used very little and nearly identically between the two scenarios.

To calculate carbon dioxide emission reductions between the reference scenario and the electrification technical potential scenario, fuel usage reductions were converted into averted emissions. To do this, emission coefficients provided by EIA at *Carbon Dioxide Emissions* Coefficients (with LPG fuel labeled "Butane/Propane Mix") were used for everything but wood (https://www.eia.gov/environment/emissions/co2_vol_mass.php, accessed 13 November 2020). The direct CO2 emission coefficient for wood was obtained from the Environmental Protection Agency at *Emissions Factors for Greenhouse Gas Inventories* (https://www.epa.gov/sites/production/files/2018-03/documents/emission-factors_mar_2018_0.pdf, accessed 13 November 2020). This direct emissions factor is likely higher than a lifetime emissions factor, which would account for the carbon stored in trees as they grow. Averted emissions for each fuel were summed for each state, giving total emissions averted per state from reduction of direct fuel usage.

Emissions from increased electricity usage due to electrification were calculated by assigning regional projections of carbon intensity of electricity production in 2050 (from EIA's *Annual Energy Outlook 2020)* to individual states. Estimates of carbon intensity were calculated for North American Electric Reliability Corporation (NERC) regions as follows:

- Projected 2050 total electricity sales and CO_2 emissions from the electricity sector were obtained for each Electricity Market Module (EMM) region from the *Annual Energy Outlook 2020* (AEO 2020) (https://www.eia.gov/outlooks/aeo/data/browser/#/?id=62-AEO2020, accessed 10 November 2020).
- Each EMM region was assigned to a NERC region using the map of EMM regions at https://www.eia.gov/outlooks/aeo/pdf/nerc_map.pdf and the map of NERC regions at https://www.nerc.com/AboutNERC/keyplayers/PublishingImages/Regions%2001JUL19.jpg. In the following cases, EMM regions that straddle more than one NERC region, were assigned to the NERC region with the greatest geographic overlap:
    - Southwest Power Pool South was assigned to MRO
    - Midcontinent ISO West was assigned to MRO
    - Midcontinent ISO Central was assigned to SERC
- Emission intensities for each NERC region were then calculated by summing the electricity sales for all the component EMM regions and dividing by the sum of the CO_2 emissions for the component EMM regions.

States were assigned to NERC regions based on the map of NERC regions, with the following exceptions:

- Alaska and Hawaii — which are not in any EMM or NERC regions — were excluded from the analysis of emissions due to increased electricity usage.
- Oklahoma and Wisconsin — which are split between two NERC regions — were assigned the emissions intensity of the EMM region in which they reside.
- Illinois and Missouri, which are split between NERC regions, were assigned the weighted averages of the carbon dioxide emission factors for the NERC regions in which they reside. The weighted averages were calculated using the share of electricity generated in each region calculated from the EIA's Form 861: Utility Data table for 2019, downloaded from https://www.eia.gov/electricity/data/eia861/ on 13 November 2020. For Illinois, utilities in the MISO balancing authority were assigned to the SERC region and utilities in the PJM balancing authority were assigned to the RF region. For Missouri, utilities in the SWPP balancing authority were assigned to the MRO region; utilities in the MISO balancing authority to SERC; and utilities in the AECI and SPA balancing authorities split evenly between MRO and SERC.

Finally, to calculate emissions from electricity generation increases due to electrification, the increased electricity usage in the electrification technical potential scenario for each state was multiplied by the emissions intensity for each state as calculated and assigned above, with standard conversions from short tons to metric tons and from terawatt-hours to kilowatt-hours. Net greenhouse gas emissions reductions for each state were calculated by subtracting the emissions of increased electricity usage from the averted emissions from reduction of direct fossil fuel use.

TABLE 4: ASSIGNMENTS OF EMM REGIONS TO NERC REGIONS AND CALCULATED EMISSIONS INTENSITY FOR 2050

NERC region	EMM regions	Projected 2050 emissions intensity (metric tons CO_2/MWh)
WECC	Western Electricity Coordinating Council Southwest	0.175
	Western Electricity Coordinating Council California North	
	Western Electricity Coordinating Council California South	
	Western Electricity Coordinating Council Northwest Power Pool Area	
	Western Electricity Coordinating Council Rockies	
	Western Electricity Coordinating Council Basin	
MRO	Southwest Power Pool Central	0.329
	Southwest Power Pool North	
	Southwest Power Pool South	
	Midcontinent West	
RF	Midcontinent East	0.353
	PJM West	
	PJM East	
	PJM ComEd	
NPCC	Northeast Power Coordinating Council/New England	0.094
	Northeast Power Coordinating Council/NYC and LI	
	Northeast Power Coordinating Council/Upstate NY	
Texas RE	Texas Reliability Entity	0.288
SERC	Florida Reliability Coordinating Council	0.319
	SERC Reliability Corporation Southeastern	
	SERC Reliability Corporation Central	
	SERC Reliability Corporation East	
	Midcontinent South	
	PJM Dominion	
	Midcontinent Central	

Appendix A: Number of homes heated with various fuels

TABLE A-1: NUMBER OF HOUSING UNITS IN EACH STATE BY HOME HEATING FUEL USED[269]

State	Total housing units	Units using utility gas	Units using bottled, tank, or LP gas	Units using fuel oil, kerosene, etc.	Units using wood	Units using other fuel	Units with no fuel used	Units using electricity	Percent of units using electricity
Alabama	1,897,576	502,880	106,166	2,384	16,377	2,114	7,389	1,260,266	66%
Alaska	252,199	122,448	4,879	77,795	12,171	3,085	1,210	30,611	12%
Arizona	2,670,441	877,561	75,036	2,905	50,942	24,834	24,263	1,614,900	60%
Arkansas	1,163,647	450,216	78,170	638	39,897	2,827	3,278	588,621	51%
California	13,157,873	8,469,893	426,530	30,373	181,624	149,545	402,298	3,497,610	27%
Colorado	2,235,103	1,529,865	107,982	1,837	35,043	22,986	10,825	526,565	24%
Connecticut	1,377,166	500,471	66,974	535,420	22,304	9,674	4,709	237,614	17%
Delaware	376,239	159,659	38,075	38,189	3,032	3,521	1,685	132,078	35%
District of Columbia	291,570	148,736	3,304	2,931	0	2,112	5,735	128,752	44%
Florida	7,905,832	368,160	65,262	9,295	11,985	19,218	147,717	7,284,195	92%
Georgia	3,852,714	1,487,548	173,271	5,442	23,072	4,423	17,386	2,141,572	56%
Hawaii	465,299	9,823	7,151	254	1,227	17,113	272,729	157,002	34%
Idaho	655,859	333,883	33,933	9,851	43,627	6,697	2,150	225,718	34%
Illinois	4,866,006	3,750,774	205,926	7,096	19,263	25,007	29,643	828,297	17%
Indiana	2,597,765	1,552,483	184,697	16,238	44,677	16,757	10,123	772,790	30%
Iowa	1,287,221	780,476	165,743	4,706	15,032	9,957	6,342	304,965	24%
Kansas	1,138,329	731,882	91,295	2,138	15,390	4,987	2,687	289,950	25%
Kentucky	1,748,732	644,977	108,053	12,525	48,551	8,188	5,196	921,242	53%
Louisiana	1,741,076	579,773	31,301	316	7,044	1,893	6,708	1,114,041	64%
Maine	573,618	44,750	69,241	344,869	53,927	10,615	2,208	48,008	8%
Maryland	2,226,767	976,786	78,176	176,841	24,667	19,779	10,872	939,646	42%
Massachusetts	2,650,680	1,385,815	98,388	646,103	32,105	26,526	12,860	448,883	17%
Michigan	3,969,880	3,031,018	335,186	39,166	105,400	37,536	17,792	403,782	10%

State	Total housing units	Units using utility gas	Units using bottled, tank, or LP gas	Units using fuel oil, kerosene, etc.	Units using wood	Units using other fuel	Units with no fuel used	Units using electricity	Percent of units using electricity
Minnesota	2,222,568	1,471,186	249,094	34,406	44,412	22,956	15,326	385,188	17%
Mississippi	1,100,229	317,472	125,039	1,503	13,671	932	3,339	638,273	58%
Missouri	2,458,337	1,225,703	222,354	5,673	74,529	9,770	7,470	912,838	37%
Montana	437,651	225,502	59,192	3,748	29,920	3,776	975	114,538	26%
Nebraska	771,444	456,589	57,234	3,126	8,869	6,186	3,583	235,857	31%
Nevada	1,143,557	664,388	29,867	5,404	14,014	10,656	6,113	413,115	36%
New Hampshire	541,396	115,248	94,024	227,725	34,512	10,746	5,280	53,861	10%
New Jersey	3,286,264	2,474,295	71,419	241,742	10,368	19,827	20,499	448,114	14%
New Mexico	793,420	490,135	49,317	1,529	56,217	14,560	2,053	179,609	23%
New York	7,446,812	4,519,999	319,576	1,393,560	114,011	104,752	83,469	911,445	12%
North Carolina	4,046,348	988,773	265,965	106,305	57,333	9,426	18,281	2,600,265	64%
North Dakota	323,519	129,531	44,922	6,600	1,116	5,196	2,641	133,513	41%
Ohio	4,730,340	3,075,761	253,741	96,389	75,416	41,963	19,673	1,167,397	25%
Oklahoma	1,495,151	762,649	100,215	2,397	22,905	11,771	4,043	591,171	40%
Oregon	1,649,352	608,187	29,180	26,802	98,494	14,869	6,735	865,085	52%
Pennsylvania	5,119,249	2,634,591	235,490	792,365	117,969	93,648	22,809	1,222,377	24%
Rhode Island	407,174	225,120	14,493	116,413	5,906	2,465	994	41,783	10%
South Carolina	1,975,915	464,662	68,110	12,243	13,860	5,494	10,651	1,400,895	71%
South Dakota	353,799	164,029	57,650	5,362	4,959	4,536	2,323	114,940	32%
Tennessee	2,654,737	830,737	98,977	8,693	42,520	4,789	8,661	1,660,360	63%
Texas	9,985,126	3,499,082	283,573	6,632	28,184	22,600	43,282	6,101,773	61%
Utah	1,023,855	827,604	23,489	826	11,231	7,460	1,606	151,639	15%
Vermont	262,767	48,826	48,270	108,658	34,473	5,571	246	16,723	6%
Virginia	3,191,847	1,041,958	135,500	131,931	60,480	13,802	14,542	1,793,634	56%
Washington	2,932,477	1,001,906	86,647	47,771	108,817	21,455	13,621	1,652,260	56%
West Virginia	728,175	290,668	38,333	19,681	39,813	9,941	1,708	328,031	45%
Wisconsin	2,386,623	1,570,313	285,657	41,457	71,833	19,436	13,927	384,000	16%
Wyoming	233,128	138,003	28,099	199	9,447	3,257	1,055	53,068	23%
Puerto Rico	1,170,982	792	9,382	173	114	5,586	1,026,514	128,421	11%

Appendix B: Emission reductions from electrification by state

TABLE B-1: 2050 CHANGES IN GREENHOUSE GAS EMISSIONS FOR RESIDENTIAL AND COMMERCIAL SECTORS IN ELECTRIFICATION SCENARIO[270]

State	Percentage of 2017 statewide emissions produced by the residential and commercial sectors	Increase in carbon dioxide emissions from electricity usage (million metric tons CO_2)	Reduction in carbon dioxide emissions from fuel use (million metric tons CO_2)	Net reduction in carbon dioxide emissions (million metric tons CO_2)
Alabama	4%	0.2	3.1	2.9
Alaska	11%	N/A	1.5	1.5
Arizona	6%	0.5	6.0	5.6
Arkansas	7%	0.6	3.3	2.6
California	12%	6.8	34.2	27.4
Colorado	13%	2.0	10.0	8.0
Connecticut	31%	0.7	5.9	5.2
Delaware	14%	0.2	0.8	0.6
District of Columbia	61%	0.3	0.9	0.6
Florida	4%	0.6	8.7	8.2
Georgia	8%	1.2	6.9	5.7
Hawaii	3%	N/A	0.8	0.8
Idaho	18%	0.6	3.0	2.3
Illinois	18%	10.7	26.8	16.1
Indiana	7%	5.2	12.8	7.7
Iowa	11%	1.8	5.1	3.2
Kansas	10%	0.8	3.7	2.8
Kentucky	5%	0.5	3.7	3.2
Louisiana	2%	0.7	3.8	3.1
Maine	30%	0.4	2.8	2.4
Maryland	20%	1.4	6.1	4.8
Massachusetts	31%	1.4	11.4	10.0

State	Percentage of 2017 statewide emissions produced by the residential and commercial sectors	Increase in carbon dioxide emissions from electricity usage (million metric tons CO_2)	Reduction in carbon dioxide emissions from fuel use (million metric tons CO_2)	Net reduction in carbon dioxide emissions (million metric tons CO_2)
Michigan	19%	9.5	22.0	12.4
Minnesota	17%	4.5	10.4	5.9
Mississippi	4%	0.1	1.8	1.7
Missouri	8%	2.2	9.1	6.9
Montana	10%	0.5	2.1	1.7
Nebraska	9%	1.0	2.9	1.9
Nevada	13%	0.5	3.6	3.1
New Hampshire	30%	0.3	2.6	2.3
New Jersey	23%	6.9	16.5	9.5
New Mexico	7%	0.5	2.9	2.4
New York	34%	4.7	40.1	35.4
North Carolina	8%	1.4	7.5	6.1
North Dakota	4%	0.7	1.5	0.8
Ohio	13%	9.6	23.5	13.9
Oklahoma	7%	0.6	4.5	3.9
Oregon	14%	1.0	5.1	4.1
Pennsylvania	14%	11.0	24.7	13.7
Rhode Island	27%	0.2	1.7	1.5
South Carolina	6%	0.5	3.2	2.7
South Dakota	12%	0.6	1.5	0.9
Tennessee	7%	0.7	5.1	4.4
Texas	3%	3.6	21.9	18.3
Utah	11%	1.0	4.8	3.8
Vermont	37%	0.2	1.3	1.1
Virginia	12%	1.7	8.4	6.7
Washington	14%	1.9	9.6	7.7
West Virginia	3%	0.5	1.7	1.2
Wisconsin	15%	7.6	14.3	6.7
Wyoming	3%	0.3	1.2	1.0

Appendix C: Change in fossil fuel usage from electrification by state

TABLE C-1: CHANGE IN 2050 FOSSIL FUEL USAGE IN RESIDENTIAL AND COMMERCIAL SECTORS UNDER ELECTRIFICATION SCENARIO[271]

State	Reduction in total diesel fuel usage (million gallons)	Reduction in total pipeline gas usage (billion cubic feet)	Reduction in total LPG fuel usage (million gallons)
Alabama	0.1	55.6	29.1
Alaska	-0.1	26.7	14.9
Arizona	0.3	103.1	80.5
Arkansas	0.0	56.5	39.8
California	3.7	608.6	249.8
Colorado	0.8	170.7	157.6
Connecticut	42.9	84.6	139.4
Delaware	3.6	14.4	7.7
District of Columbia	5.4	15.6	5.8
Florida	13.0	152.0	62.3
Georgia	24.2	119.2	60.1
Hawaii	0.0	14.7	2.9
Idaho	0.2	50.3	46.9
Illinois	0.4	460.1	386.9
Indiana	0.3	220.1	185.2
Iowa	6.2	82.3	117.2
Kansas	5.8	59.7	81.9
Kentucky	0.2	66.7	33.9
Louisiana	0.0	66.3	40.1
Maine	16.8	40.0	68.2
Maryland	28.8	104.9	58.3
Massachusetts	80.3	163.9	272.5
Michigan	-0.2	376.6	327.7

State	Reduction in total diesel fuel usage (million gallons)	Reduction in total pipeline gas usage (billion cubic feet)	Reduction in total LPG fuel usage (million gallons)
Minnesota	12.7	168.4	248.6
Mississippi	0.1	31.8	16.8
Missouri	15.4	146.4	210.5
Montana	0.2	36.5	33.5
Nebraska	3.5	47.1	66.3
Nevada	0.2	60.5	51.3
New Hampshire	18.9	37.7	63.9
New Jersey	156.9	266.4	78.4
New Mexico	0.2	49.0	44.2
New York	372.3	652.1	194.6
North Carolina	27.7	129.3	67.9
North Dakota	1.5	24.5	36.4
Ohio	0.4	404.1	336.2
Oklahoma	0.0	76.9	54.2
Oregon	0.6	90.8	44.1
Pennsylvania	172.9	410.8	122.0
Rhode Island	10.8	24.3	40.0
South Carolina	10.3	54.9	28.5
South Dakota	1.9	23.9	34.5
Tennessee	0.2	92.1	46.2
Texas	0.1	378.4	235.6
Utah	0.4	81.9	76.3
Vermont	10.8	18.1	30.3
Virginia	39.9	143.7	77.8
Washington	1.1	171.0	87.2
West Virginia	5.9	29.5	17.2
Wisconsin	0.0	244.7	208.3
Wyoming	0.1	21.1	19.0

Appendix D: Increase in electricity demand by sector and state

TABLE D-1: INCREASE IN 2050 ELECTRICITY DEMAND IN THE RESIDENTIAL AND COMMERCIAL SECTORS FROM A REFERENCE ELECTRIFICATION SCENARIO TO AN ELECTRIFICATION TECHNICAL POTENTIAL SCENARIO[272]

State	Increase in residential electricity usage (TWh)	Increase in commercial electricity usage (TWh)	Increase in total electricity usage (TWh)
Alabama	-1.5	2.1	0.6
Alaska	1.8	0.7	2.6
Arizona	-0.3	2.9	2.6
Arkansas	-0.2	2.3	2.0
California	16.2	22.7	38.9
Colorado	7.5	4.1	11.6
Connecticut	5.5	1.9	7.4
Delaware	-0.1	0.6	0.6
District of Columbia	-0.1	0.9	0.9
Florida	-8.2	9.9	1.7
Georgia	-2.1	5.8	3.7
Hawaii	0.0	0.9	0.9
Idaho	2.2	1.3	3.5
Illinois	21.9	9.4	31.3
Indiana	10.2	4.4	14.7
Iowa	3.9	1.7	5.6
Kansas	1.4	1.2	2.6
Kentucky	-0.5	2.1	1.6
Louisiana	-0.9	3.2	2.2
Maine	3.1	1.1	4.3
Maryland	-0.2	4.1	3.9
Massachusetts	10.8	3.6	14.4

State	Increase in residential electricity usage (TWh)	Increase in commercial electricity usage (TWh)	Increase in total electricity usage (TWh)
Michigan	19.6	7.4	27.0
Minnesota	9.7	4.0	13.7
Mississippi	-1.0	1.2	0.3
Missouri	4.0	2.6	6.6
Montana	1.6	1.1	2.7
Nebraska	2.1	0.9	3.0
Nevada	1.2	1.6	2.8
New Hampshire	2.7	0.9	3.6
New Jersey	12.0	7.7	19.7
New Mexico	1.5	1.2	2.7
New York	31.8	18.4	50.1
North Carolina	-1.6	5.8	4.3
North Dakota	1.5	0.6	2.1
Ohio	19.1	8.3	27.3
Oklahoma	-0.4	3.1	2.7
Oregon	3.1	2.6	5.7
Pennsylvania	19.8	11.4	31.2
Rhode Island	1.6	0.5	2.1
South Carolina	-1.1	2.6	1.5
South Dakota	1.3	0.6	1.8
Tennessee	-1.1	3.2	2.1
Texas	-5.6	18.0	12.3
Utah	3.4	2.0	5.5
Vermont	1.4	0.6	1.9
Virginia	-0.4	5.8	5.5
Washington	6.2	4.6	10.8
West Virginia	0.4	1.1	1.5
Wisconsin	13.7	6.3	20.0
Wyoming	1.0	0.7	1.6

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