Electric Buildings

How to repower where we live, work and learn with clean energy

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December 2019

Acknowledgments

The authors thank David Houghton, Karl Rabago of the Pace Energy and Climate Center, Hans Detweiler, Margaret Cherne-Hendrick of Fresh Energy, Edward Mazria of Architecture 2030 and Rachel Golden of Sierra Club for their review of drafts of this document, as well as their insights and suggestions. Thanks also to Tony Dutzik, Susan Rakov and Linus Lu of Frontier Group for editorial support.

Environment America Research & Policy Center and U.S. PIRG Education Fund thank the Scherman Foundation and the Energy Foundation for making this report possible. The recommendations are those of Environment America Research & Policy Center and U.S. PIRG Education Fund. The authors bear responsibility for any factual errors. The views expressed in this report are those of the authors and do not necessarily reflect the views of our funders or those who provided review.

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Executive summary

To prevent air and water pollution and the worst impacts of global warming, America must move toward meeting its energy needs with 100 percent renewable energy. Getting there will require that we get the most out of every bit of energy we use – and that we end the burning of 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 fossil fuels like gas, heating oil and propane in our buildings will reduce climate change and air pollution.

New and improved technologies are putting clean, efficient electric space heating, water heating and appliances within the reach of most American households. **Unfortunately, common barriers, including knowledge gaps and high upfront costs, often make the decision to switch from fossil fuels to electricity challenging for many homeowners and businesses.**

Local, state and federal governments should take the next step toward repowering America with 100 percent renewable energy by accelerating the transition of our homes and businesses away from fossil fuels and toward electric power. Adopting smart public policies to encourage electrification of buildings, energy efficiency improvements, and installation of distributed renewable energy sources such as solar photovoltaic panels and solar hot water systems can help the nation to achieve the goal of ending the direct burning of fossil fuels by mid-century.

Fossil fuel burning in homes and businesses contributes to global warming and harms our health.

- Three out of every four American homes use fossil fuels directly for space heating, water heating or appliances.[2] Direct burning of fossil fuels accounts for more than half of all energy used in homes and at least 34 percent of all energy used in commercial buildings.[3]
- In 2017, fossil fuel combustion in U.S. homes and businesses produced 533 million metric tons of greenhouse gases*, accounting for 8 percent of total U.S. greenhouse gas emissions and equivalent to the emissions of over 115 million cars.[4]
- A 2017 National Renewable Energy Laboratory (NREL) study estimates that full electrification of buildings could cut non-electrical uses of fossil fuels in the United States by more than one-fifth by 2050.[5]
- Burning fossil fuels within our homes creates indoor air pollution, which contributes to the development of respiratory diseases, heart disease and cancer.[6]

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

* Actual emissions associated with fossil fuel use in buildings are likely much higher, as this figure does not account for the impact of leaked methane during the production and transmission of natural gas.

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 and ground and move it around a building, have improved dramatically in recent years.[8] Geothermal heat pumps function well in all climates, and air-source heat pumps can now function effectively down to -12°F.[9] 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.[10]
- **Water heating** – Heat pump, electric resistance and solar thermal water heaters can all heat water without the direct use of fossil fuels. New technologies are making electric technologies more efficient and cost-effective. Water heat pumps can be up to five times as efficient as a gas-powered water heater.[11]
- **Appliances** – Highly efficient electric appliances can replace fossil-fueled versions and are often more effective. Electric induction cooktops are faster, cleaner, more precise and safer than a gas range.[12]

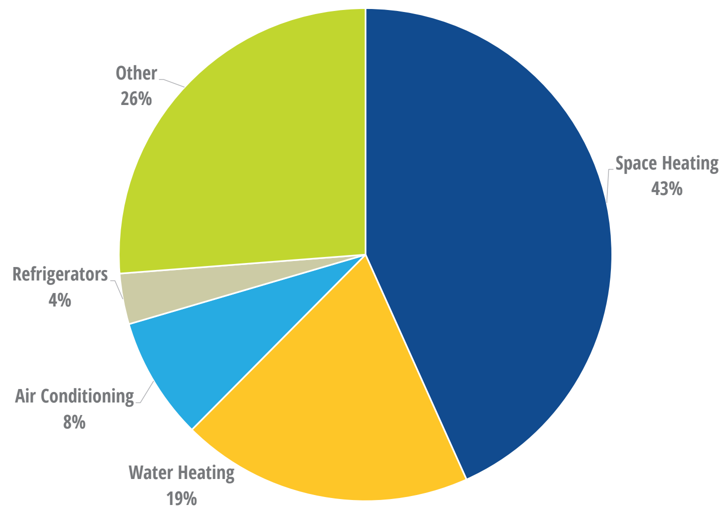

Figure ES-1: U.S. Residential Energy Consumption by End Use[7]

Building electrification often makes sense for consumers.

- Electric heat pumps are already cost-effective for new construction and for some building retrofits.[13] One study found that heat pump installation during new construction reduced lifetime costs for consumers in several areas of the country – including "cold" climate zones.[14] In these new construction scenarios, consumers opting for heat pump installation over fossil fuel heating equipment can save between $2,000 and $13,700 for space and water heating over a 15-year period.[15]
- Replacing an existing fossil fuel furnace with an electric heat pump is also financially beneficial in some circumstances.[16] 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 AC unit are at the end of their useful lives.[17]
- Building electrification allows building owners to take advantage of falling prices for clean electricity and benefit fully from installing solar PV panels or subscribing to community solar projects.[18] 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.[19]

Energy efficiency, energy storage and small-scale renewable energy technologies like solar power can help maximize the benefits of electrifying our buildings.

- **Energy efficiency** measures – such as reducing heating and cooling loads and installing high-efficiency systems – can save energy, money and ease the impacts on the electric grid from building electrification.[20]

- **Energy storage** technologies, such as battery storage systems, energy management systems and demand response appliances enable homes and businesses to match electricity demand with the availability of low-cost, renewable energy.[21]

- **Solar energy systems** provide clean, stable, low-cost electricity, which can help offset the adoption costs of all-electric appliances. By electrifying buildings, homeowners and businesses can host more solar capacity, increase the share of solar electricity used on-site, and improve the value proposition of "going solar."[22]

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

- Contractors are often unfamiliar with current technologies and foster a perception that electric heat pumps and other electric appliances are expensive and unreliable.[23]

- 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.[24]

- While falling prices have made electric systems an affordable and sustainable option for new buildings, the high capital costs associated with retrofitting buildings may mean that electrification is not always financially viable without substantial incentives.[25]

- Some energy efficiency programs offer minimal rebates or incentives for electrification and offer competing rebates for replacement of existing fossil fuel systems with more efficient versions, potentially slowing the transition to technologies that can be truly zero-emission.[26]

- 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 percent renewable energy system by 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.

- **Ban fossil fuels in new construction.** Electric heating and hot water systems are often cost-effective in new construction. Several cities, including San Jose, California, have used building codes to ban new buildings from using gas.[27] Cities should require new buildings to be powered exclusively by electricity and use energy codes to encourage or require the development of zero net energy or zero net carbon buildings, which receive their energy from renewable sources.[28]

- **Implement rebate programs and low-cost financing.** To alleviate the high upfront costs of building and appliance retrofits, policymakers should offer rebates, low-interest loans and innovative financing options to homeowners, contractors and builders for electric retrofits.

- **Create and expand tax incentives for electrified buildings.** Some tax breaks on the federal and state levels already exist for buildings that are energy efficient and/or utilize electric technology.[29] Several states have implemented property tax exemptions, which exclude any upgrades that homeowners make, such as a geothermal heat pump, from their property value for tax purposes.[30] The expansion of existing tax credits and exemptions, as well as the creation of new tax incentives specifically for the installation of electric technologies, could encourage more building owners to build or transition to fully electric systems.

- **Require transparency about building energy use.** Mandatory reporting about the energy source and performance of buildings helps ensure that any investments that owners make to improve efficiency and install electric systems are reflected in the building's value. Austin, Texas and New York City, among other cities, require that every building complete an energy efficiency assessment and disclose the results prior to its sale.[31]

- **Educate developers, contractors and consumers about options for, and benefits of, electrification.** Information is crucial for home and building owners to feel comfortable transitioning to fully electric systems. 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. Similarly, policymakers should encourage the creation of education and training programs for developers and contractors to familiarize them with modern electric heating, hot water systems, and sustainable design.

Introduction

Renewable energy is on the rise across America.

Today, America produces 40 times more solar power than it did in 2009 and three times as much wind energy.[32] Energy from the wind and sun now make up nearly 10 percent of the nation's electricity supply.[33] At the same time, thanks in part to improvements in energy efficiency, the amount of energy consumed per capita has declined by 7.8 percent since 2007.[34] 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 opportune time. In order to avoid the worst impacts of climate change, scientists say we must virtually eliminate carbon pollution from the burning of fossil fuels by mid-century.[35] Transitioning to an electricity system powered by 100 percent renewable electricity can enable us to reach that goal.

But there is a problem. While America's electricity system is increasingly powered by clean energy, the systems that heat our homes and businesses aren't. 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.[36] 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 the transition to electric homes and businesses easier and more affordable than ever before. Electric technologies are less expensive than fossil fuel alternatives in almost all scenarios for new construction.[37] 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.[38]

The rise of renewable energy and 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. This future can begin now. 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 and support, 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 a future of 100 percent clean, renewable energy. The good news is that renewable energy is booming: America produces almost five times as much renewable electricity from the sun and wind as it did in 2009, and currently wind and solar energy provide nearly 10 percent of the country's electricity.[39] Seven states nationwide, Washington D.C. and Puerto Rico have now committed to a future of 100 percent clean electricity.[40]

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.

Global warming

The United States must reduce its 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°C and avoid the worst impacts of global warming, the U.S. and other developed nations must reduce CO_2 emissions by at least 45 percent below 2010 levels by 2030 and reach net zero carbon pollution by 2050.[41]

To achieve that goal, 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 2017, fossil fuel combustion in U.S. homes and businesses produced 533 million metric tons of greenhouse gases, accounting for 8 percent of total U.S. greenhouse gas emissions and equivalent to the emissions of over 115 million cars.[42] Since 1990, emissions from fossil fuel combustion in buildings have stayed relatively constant.[43] While energy efficiency gains have prevented emissions from increasing, even as the number of homes and businesses has grown, 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.

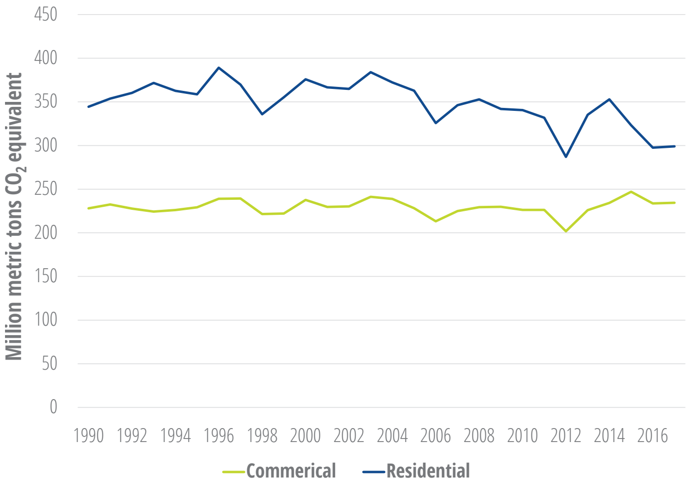

Figure 1: Greenhouse Gas Emissions from Fossil Fuel Combustion in Residential and Commercial Sectors[44]

Greenhouse gas emissions related to fossil fuel use in homes and businesses may be even greater than these numbers convey. Methane is up to 84 times more potent 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.[45] In recent years, research has revealed higher-than-expected rates of leakage of methane – the key component of natural gas.

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 natural gas systems in homes and businesses, as opposed to natural sources or landfills.[46] In 2016, the EPA estimated methane emissions for these five urban areas to be about 370,000 tons. This massive underestimation likely resulted from the fact that the EPA only includes leaks from the gas distribution system, not leaks directly from homes and businesses.[47]

By replacing the direct combustion of fossil fuels with systems powered by electricity, America can take full advantage of an increasingly clean electric grid. A 2017 National Renewable Energy Laboratory study estimates that full electrification of buildings could cut non-electrical uses of fossil fuels in the United States by more than one-fifth by 2050.[48]

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 pages 19-20.) Use of these technologies can help to accelerate the clean energy transition in other parts of the economy by increasing the ability of the grid to make effective use of renewable energy. These technologies have also been shown to reduce strain on the grid at times of peak demand, making widespread electrification easier and lowering costs for ratepayers.[49]

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, which can exacerbate respiratory issues and lead to heart disease and cancer.[50] Exposure to these pollutants is even worse without the usage of exhaust hoods, or with improperly sized hoods. In a study done by the Lawrence Berkeley National Laboratory and Stanford University, researchers created a model to estimate 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 percent to indoor nitrogen dioxide concentrations and 30 percent to indoor carbon monoxide concentrations. In the winter, gas burners add 35-39 percent to indoor nitrogen dioxide concentrations and 21 percent to indoor carbon monoxide concentrations. [51] 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, which produce nitrogen oxides (NO_X), sulfur oxide (SO_X) and small particulate matter ($PM_{2.5}$).[52] These pollutants have been found to cause respiratory, cardiac and neurological damage.[53] One study estimated that 12 percent of America's urban air pollution from particulate matter was caused by the burning of fossil fuels in buildings.[54]

The supply chain to provide fossil fuels to our buildings also has negative health effects. Fracking for gas and oil produces harmful air pollution and has the potential to contaminate drinking water.[55] Leakage from gas pipelines not only emits climate-altering methane, but also poses a physical danger to workers and people nearby. Between 2008 and 2015, there were 531 injuries and over 100 deaths from incidents involving the transportation of gas.[56]

Electrifying America's homes and businesses can clear our air, 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 – and in doing so, deliver meaningful improvements to public health.

Fossil fuels power most of our nation's buildings

Until recently, running appliances off electricity was not more sustainable than directly burning fossil fuels in the home. During the 20th century, coal was the dominant fuel for electricity generation, one of the dirtiest and most polluting fossil fuels.[57] In fact, there was even a large push to run all appliances off gas, as it was viewed as less polluting and more sustainable.[58]

But this is no longer true. The electricity grid is becoming cleaner every year and outfitting a building to run on electricity allows it to take advantage of an increasingly clean power source. If the future is going to be carbon-free, it will also have to be electric.[59]

In order to end carbon pollution by mid-century, our nation will need to electrify millions of buildings that currently are powered by fossil fuels. 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.[60]

Fossil fuel use in homes

Currently three out of every four American homes directly burn fossil fuels for heating, hot water or for appliances, such as gas stoves.[61] More than half of all home energy usage currently comes from burning fossil fuels on-site.[62] 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.

Sources of fossil fuel use

According to the U.S. Energy Information Administration, end-use residential energy consumption amounted to about 9.1 quadrillion British thermal units (quads) in 2015.[63] Energy consumption associated with space heating and water heating accounted for nearly two-thirds of residential energy usage.[64] Air conditioning and refrigeration accounted for another 8 percent and 3.3 percent respectively, with end uses like lighting, clothes washers and dryers, TVs and cooking appliances making up the rest of U.S. residential energy usage (see Figure ES-1).[65]

Together, space and water heating account for the highest proportion of energy consumed by U.S. households and currently rely heavily on fossil fuels. In 2015, the U.S. Energy Information Administration found that around 80 percent of the energy used for space and water heating in U.S. homes was from the direct burning of fossil fuels.[66]

Central heat from furnaces and boilers, typically relying on burning natural 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.[67]

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 usage is in single-digit percentage points, and fuel oil is only significantly used in the Northeast, with the U.S. Energy Information Administration estimating that the Northeast alone is responsible for 85 percent of heating oil sales.[68]

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 12,100 pounds for natural gas. With the current electric grid sourcing 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.[69] 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.

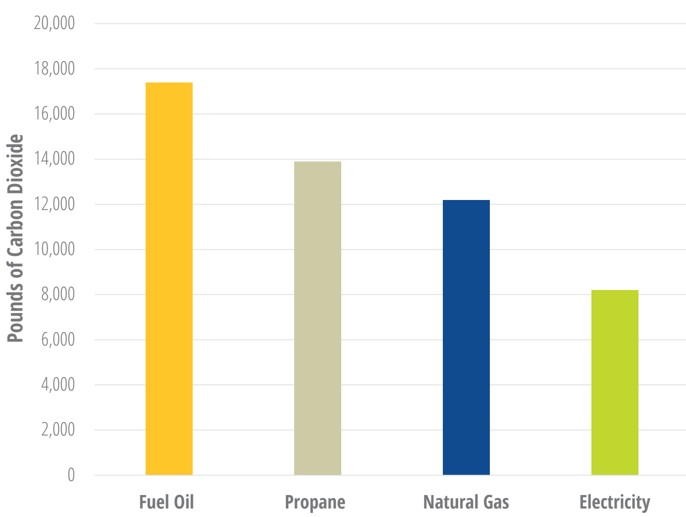

Figure 2: Annual Carbon Emissions for Furnaces in Providence, RI by Fuel Source[70]

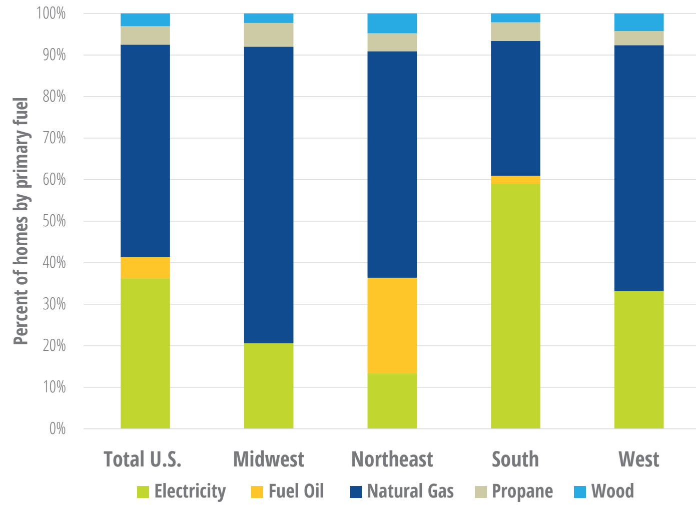

Figure 3: Primary Fuel Used for Residential Space Heating by Region[78]

Electrifying 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 more than $6,000 compared to heating oil and nearly $14,000 compared to propane.[71]

While households using fuel oil or propane for space and water heating account for fewer than 10 percent of all U.S. households, their carbon emissions make up more than 20 percent of all space and water heating-related emissions.[72] Switching from fuel oil to electricity represents "low-hanging fruit" with immediate cost savings for homeowners and significant emission reductions for the public.

Natural gas – Homes and buildings in the West, Midwest, and Northeast are more likely to rely on natural gas for water and space heating.[73] Gas remains a popular heating fuel because of its current low price, and remains the dominant fossil fuel in every region of the country.[74] Retrofitting existing buildings powered by natural gas to run on electricity is not currently cost-effective in much of the country.[75]

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.[76] As a result, it is critical both to power all new buildings with electricity and to transition buildings 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 natural gas infrastructure.[77]

Water heating in homes

Water heating is the second largest end-use of energy in homes.[79] As with space heating, natural 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.[80]

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 storage 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.[81] 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.[82] However, they are much less common than conventional tank water heaters, currently comprising around 3 percent of water heaters in American homes.[83]

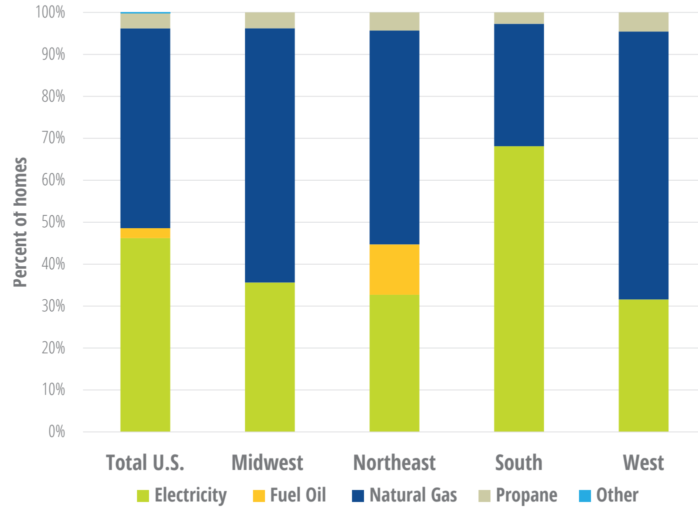

Figure 4: Primary Fuel Used for Residential Water Heating by Region[84]

Fossil fuel use in commercial buildings

In 2012, the U.S. Commercial Buildings Energy Consumption Survey found that commercial buildings consumed 6.9 quadrillion British thermal units (quads) of energy.[85] Of the energy used in commercial buildings, at least 34 percent came from direct combustion of fossil fuels.[86] 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.[87]

However, for cooking and space and water heating, commercial buildings still rely heavily on natural gas.[88] 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.

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, operating costs for electric systems tend to be lower, 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.[89]

Heat pumps

Heat pumps are among the most widely installed electric-powered space and water heating systems and have a high potential for more widespread installation due to recent improvements in efficiency in colder climates.[90]

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 heating mode in the winter as well as in reverse, providing cooling in the summer.[91]

Heat pumps fall into two categories: air-source heat pumps and ground-source, or geothermal, heat pumps. Air-source heat pumps pull heat from the surrounding ambient air and use it to heat (or cool) the building.[92] Geothermal heat pumps pull the earth's relatively stable, year-round temperature from underground, but otherwise work similarly to air-source heat pumps.[93] Installation of geothermal heat pumps is more costly than that of air-source heat pumps, as piping must be installed underground, but they offer significantly higher efficiency and could potentially lower long-term energy costs.[94] Geothermal systems can also capture waste heat to use for water heating, further reducing emissions and costs.[95]

Heat pumps are much more efficient than burning fossil fuels for heat. The coefficient of performance (COP), or the ratio of energy out divided

An outside unit of an air-source heat pump.

by energy in, for air-source heat pumps range between 2.2 to 3.0, meaning that for every unit of electricity used to power the heat pump, 2.2 to 3 units of heat will be transferred into or out of the home. Geothermal heat pumps, by extracting the stable temperature of the earth, can achieve even higher efficiency metrics – often reaching COPs of 3.0 to 6.0.[96] By comparison, electric resistance heating has a COP of 1.0.[97] Modern gas boilers and propane boilers both have average COPs of 0.93.[98] Older fossil fuel furnaces are often even less efficient, and can lose up to 40 percent of the heat they produce.[99]

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.[100] A Rocky Mountain Institute 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 -12°F.[101]

Water heating

The two most common electric water heating technologies are electric resistance water heaters and heat pump water heaters. Electric resistance (ER) water heaters consist of a tank with submerged electric heating elements. These heaters usually last longer than the tanks of fossil fuel-fired heaters.[102]

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.[103] Research has indicated that heat pump water heaters are a very efficient way to provide water heating.[104] Heat pump water heaters can be up to five times as efficient as a gas-powered water heater.[105]

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.[106]

Other, less common options for electric water heating include carbon dioxide-based heat pump water heaters, thermal exchange water and space heating (which uses heat from wastewater), single-unit outdoor heat pumps, and tankless electric units.[107]

Electric appliances

Fossil fuel powered appliances like stoves 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 percent 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, heat energy is generated in the pan as the electric currents run through the metal.[108] 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.[109] 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.[110]

In addition to cooking, clothes dryers, pool heaters and hot tub heaters are sometimes powered by fossil fuels, so efforts to further electrify these appliances will assist in the complete electrification of the building sector.[111]

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.[112] Solar thermal energy has been used for decades to provide clean space and water heating.[113]

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 power plant that provides heating, cooling and sometimes electricity.[114] 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.[115]

The primary reason why campuses create district energy systems is for efficiency gains. Just like with heat pumps, district energy systems can achieve incredibly high coefficient of performance (COP) ratings.[116] For instance, Stanford University reports that its district energy system achieves a combined annual COP of 6.3.[117]

The use of district energy systems is still relatively uncommon, with only 47,000 commercial buildings in the United States sourcing their primary heating from district systems as of 2012 – comprising less than 1 percent of all commercial buildings in that year.[118]

Generally, district energy systems are powered off fossil fuels.[119] 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.[120]

New and emerging technologies can maximize the benefits of electrification

Building electrification allows the potential of a renewable grid to be fully realized. 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 easily transition to an economy powered by 100 percent renewable energy.

These technologies will become increasingly important as electrification spreads across the building and transportation sectors and raises demand on the electric grid. Projections from NREL show that with widespread electrification, electricity consumption could reach 6,500 terawatts by 2050, a more than 60 percent increase above current levels.[121] 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-fired 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 systems and ventilation systems, as well as incentives to install more efficient lighting.[122] 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.[123]

Beyond larger-scale improvements, home and building owners can also focus on smaller steps, such as upgrading to energy-efficient appliances. Lighting, for example, is an area in which technology has already made great strides. Increasing the use of efficient bulbs like LEDs could greatly reduce unnecessary energy usage. LED bulbs use at least 75 percent less energy than traditional incandescent light bulbs and last about 25 times longer, saving consumers time, money and effort. 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 at today's electricity prices.[124]

High-efficiency appliances like washing machines, dryers and refrigerators can also reduce a home's electricity demand.[125] After space heating and water heating, appliances are the third-largest source of energy use in a home, accounting for nearly a tenth of home energy consumption.[126]

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 way 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 or other forms of distributed renewable energy, as it enables buildings to continue to use locally generated renewable electricity even after the sun goes down.

Behind-the-meter energy storage systems such as battery storage grew substantially in 2018, surpassing front-of-meter storage capacity (industrial batteries, pumped storage, etc.) for the first time.[127] 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.[128] 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.[129]

Another cost-effective behind-the-meter energy storage option is the grid-interactive electric water heater. Preheating 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.[130]

Looking ahead, the rapid adoption of electric vehicles presents a new opportunity for energy storage. 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 through bi-directional power flow.[131]

"Behind-the-meter" battery storage at an apartment complex in Los Angeles County, California.

This means that instead of EV batteries just receiving energy from the electricity grid, they can also provide stored energy back to the grid when needed.[132] Combined with the development of smart, integrated electric grids, the batteries in electric vehicles can be used to provide power to the grid at times of peak demand and serve as a source of backup power in an emergency.[133]

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 when 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.[134]

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.[135] In return for reducing their thermostats during times of high demand, consumers receive a smaller electricity bill and often a rebate from the utility company.[136] 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 reduce their electricity bills by 10-40 percent.[137]

On-site renewable energy technologies

On-site renewable energy production, such as rooftop solar panels or a community solar installation, can help spur electrification by allowing more of a building's energy load to be met by affordable, clean energy. It also helps 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 consumers 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.[138] 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.[139] The production of renewable energy on-site can also help bring down electricity bills for consumers as they transition to electric systems.[140]

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, energy-efficient lighting and appliances to slash overall energy consumption, while generating 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.[141]

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.[142] The production usually comes from rooftop solar panels and energy usage is cut through extensive efficiency improvements.[143]

Zero net carbon (ZNC) buildings are those that are highly efficient and receive all their energy from carbon-free sources.[144] Unlike ZNE buildings, ZNC buildings can procure their renewable electricity by purchasing it through an off-site source.[145] This makes mandating ZNC buildings easier for many jurisdictions, as the technology already exists to make them affordable and a realistic option in new construction.

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.[146]

Lower lifetime costs for new construction

The Rocky Mountain Institute (RMI) found that in almost all scenarios, electrification is the most cost-effective option for consumers building a new home.[147] The study examined the costs of incorporating electric technologies in buildings in four cities (Oakland, Houston, Providence and Chicago) and found that in every city, installing electric technologies in new construction saved consumers money over installing gas or oil systems.[148]

RMI found that in every city studied, heat pump installation reduced lifetime costs for consumers in new construction compared to similar new construction using natural 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 $2,000 and $13,700 in net-present cost for space and water heating over a 15-year period.[149]

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.[150] Nearly 10 percent of the nation heats their homes primarily using heating oil or propane, two of the dirtiest and most expensive fossil fuels.[151] 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 percent.[152]

Switching from existing gas heating systems to electricity is currently not cost-effective in many parts of the country.[153] Studies from both the U.S. Department of Energy and the 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 AC unit are at the end of their useful lives.[154] But even in these cases, the high upfront costs of retrofitting may not be recouped for years. The 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 natural gas.[155]

However, with a typical lifespan of 30 years for gas furnaces, continuing to replace failing gas heating systems with new fossil fuel-burning systems 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.

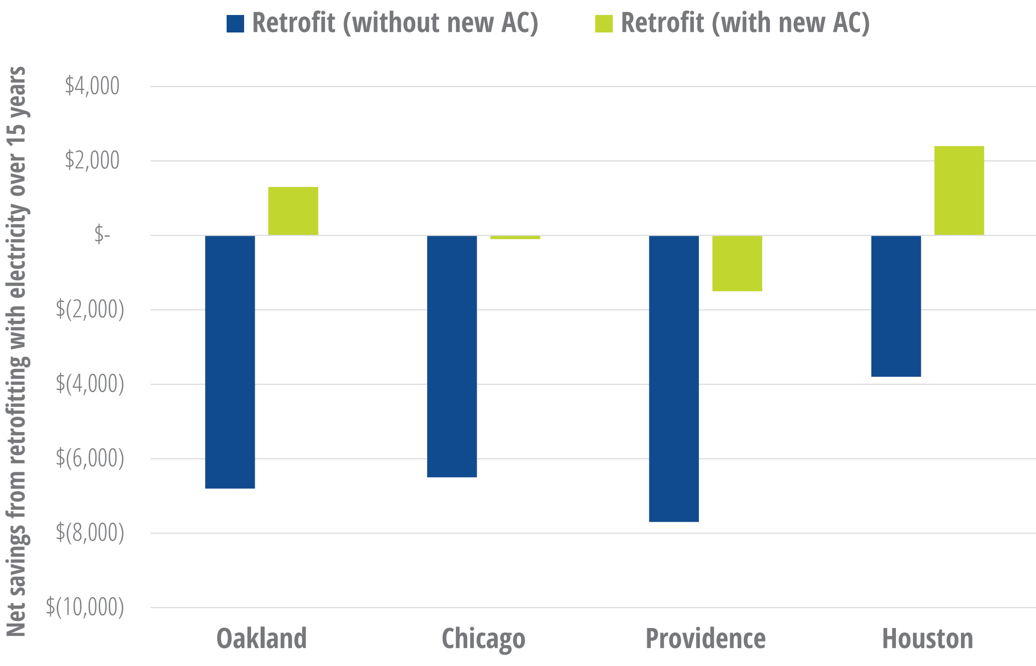

Figure 5: Costs and Savings from Retrofitting with Electricity for Space and Water Heating Compared to Natural Gas[156]

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 that 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.[157] 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, like smart preheating of building spaces and hot water, can help a solar PV system meet even more of a house's electricity demand.[158] 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 percent clean, renewable energy system.

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.[159]

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.[160] 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.[161]

Lack of familiarity with the technology is not just a barrier with consumers, but also with the contractors tasked with recommending and installing new technologies in homes and buildings.[162] 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.[163]

Higher capital costs of retrofitting

High upfront capital costs are sometimes a barrier to retrofitting buildings to run on electricity.[164] These costs can deter customers from electrifying their buildings.

While prices for electric heating systems vary, in general, ductless air-source heat pumps cost between $3,500 to $5,000 for each unit, and a central air heat pump system can run anywhere from $12,000 to $20,000.[165] Additionally, buildings may need upgrades in electricity services 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.[166] To upgrade electricity services 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.[167]

Addressing high capital costs requires a range of approaches. One approach is to prioritize replacement of heating and air conditioning (AC) 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 point of replacement 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 AC 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 AC unit are both worn out, electrification retrofits are cost-effective in nearly all cases for oil and propane and over half of homes that run off natural gas.[168] 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.

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 and the costs associated with subsidizing building electrification.

Accommodating the increased electricity demand from building electrification does present its own set of challenges.[169] Studies show that while electrifying a handful of buildings will have a minimal impact on the grid, widespread building electrification could significantly increase electricity demand.[170] Combined with the electrification of the transportation sector, analysts predict that widespread adoption of electric technologies could increase electricity demand by 85 percent by 2050.[171] Electricity consumption patterns and the timing of peak demand may also shift dramatically.[172]

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 can help accommodate increased demand in both the short- and long-term.[173] These upgrades will eventually be necessary for widespread electrification in both the buildings and transportation sectors.[174] 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.[175] Additionally, further adoption of demand-response technologies, battery storage and on-site renewable energy resources can instill more flexibility in the electricity grid, which can allow it to better absorb additional demand.

Costs of incentives and policy reforms

Fully electrifying our building sectors 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 incentivize electrification. Utility and state programs often offer generous incentives to upgrade an inefficient natural gas heating system to an efficient one, but fewer incentives to switch to an electric system.[176] 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.[177]

Some states have begun to adjust their approach, establishing generous incentives for owners to convert to electricity from dirtier fossil fuels. Massachusetts, for instance, now gives rebates of up to $7,200 to building owners that switch to electric heat pumps from heating oil.[178]

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, and 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 avoid the worst impacts of global warming and embrace a future of 100 percent 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 policies that require electric systems in new construction. Constructing new buildings with fully electric systems is already cost-effective in most circumstances. Several cities, including San Jose and Berkeley, California, have used building codes to ban new natural gas infrastructure.[179]

Building codes are local or state ordinances that mandate certain standards for building construction.[180] 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 become familiar with new technologies before they become mandated.[181]

Building codes can also be used to incentivize, and eventually require, the construction of zero net energy (ZNE) or zero net carbon (ZNC) buildings.[182] ZNE buildings are highly energy-efficient buildings that produce as much energy as they consume through renewable sources on-site.[183] ZNC buildings are similar, but can source their renewable energy from off-site locations.[184] Already many states and local jurisdictions have aspects of ZNE and ZNC buildings as part of their codes.[185] In California, for example, most new single-family homes and some multi-family buildings must install a solar PV system.[186] The state also has strict energy efficiency standards for new buildings.[187] Eventually, states and cities can utilize these codes to require that all new construction conforms with ZNE and ZNC standards.[188]

Implement rebate programs and low-cost financing. While a fully electric building usually costs less to power than a building using natural gas or oil over a period of several years, the upfront cost can often be higher. To incentivize the transition to electric infrastructure, government programs should be established which offer rebates 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.[189] 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 customers looking to electrify and switch from oil to a heat pump.[190] Through this policy, consumers currently using the dirtiest and most inefficient fuels will have the largest incentives to electrify.

Utilities and governments should also look to create "inclusive financing" programs, which provide the upfront investment for homes to electrify and then recoup the costs through payments on subsequent electric bills.[191]These programs are already being used to provide home owners with the ability to make energy efficiency upgrades and purchase rooftop solar installations.

Create and expand tax incentives for electrified buildings. There are already a few tax incentives on the federal and state levels for buildings that are energy efficient and/or utilize electric technology.[192] Several states have implemented property tax exemptions, which exclude any upgrades that homeowners make, such as the installation of geothermal heat pumps, from their property value for tax purposes.[193] 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 was a federal tax deduction that allowed commercial building owners to reduce their tax bill if the building saved at least 50 percent of the heating and cooling energy in relation to minimum standards set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).[194] However, this tax deduction was always temporary, being renewed every few years in a tax extension bill and applied retroactively.[195] 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 incentive 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 refunds 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.[196] This could help encourage more widespread electrification of our building sector and appeal to building owners that may not have been able to benefit from a non-refundable tax credit.

Require transparency about energy efficiency to create home and building value. 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.

Berkeley, California, New York City and Austin, Texas, among other cities, have implemented programs to uncover energy savings opportunities in the city's buildings and give buyers information about the efficiency of buildings.[197] 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.[198] 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.[199] 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.[200]

This program also gives people looking to buy a home or building more information about the energy performance of the building, enabling would-be buyers to factor it into their decisions. Most places in the U.S. do not have policies that require disclosure of information on a building's energy use, so when homeowners choose to electrify their systems and appliances, or make energy-saving upgrades on their homes, the value of these projects are not reflected in home prices and the investments are effectively lost.[201] 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 before they sold their properties.[202] 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.

Educate contractors and consumers about options for, and benefits of, electrification. Information on electrification can be extremely useful for consumers and contractors, as it can sometimes be difficult to understand the possible benefits and costs that result from switching to new and unfamiliar technologies.

In an effort to reduce greenhouse gas emissions, the city of Boulder, Colorado, has entered into programs to promote building electrification and make installation of electric technologies like heat pumps easier and more affordable for families. The city has developed a system which 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 has 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, and Boulder witnessed a three-fold increase in heat pump installations within its first year.[203]

Contractors and builders can also benefit from information and education when it comes to new electric technologies. One of the common barriers that keep contractors from recommending electric systems is a lack of experience installing and maintaining electric technologies.[204] Government-supported training programs and seminars could help increase awareness of these electric technologies among contractors, as well as help improve the quality of their installations and maintenance.[205]

Notes

1. Rob Sargent, Jonathan Sundby and Gideon Weissman, Environment America Research & Policy Center and Frontier Group, *Renewables on the Rise 2019,* August 2019, downloaded at https://frontiergroup.org/reports/fg/renewables-rise-2019.

2. U.S. Energy Information Administration, *One in Four U.S. Homes is All Electric,* 1 May 2019, archived at http://web.archive.org/web/20190923052739/https://www.eia.gov/todayinenergy/detail.php?id=39293.

3. U.S. Energy Information Administration, *Use of Energy Explained: Energy Use in Homes,* 28 September 2018, archived at http://web.archive.org/web/20190925011236/https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php; U.S. Energy Information Administration, *Use of Energy Explained: Energy Use in Commercial Buildings,* 28 September 2018, archived at http://web.archive.org/web/20190925011236/https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php.

4. Environmental Protection Agency, *Greenhouse Gas Inventory Data Explorer,* accessed on 18 October 2019, archived at https://web.archive.org/web/20191125132550/https://cfpub.epa.gov/ghgdata/inventoryexplorer/; total U.S. emissions: Environmental Protection Agency, *Sources of Greenhouse Gas Emissions,* accessed on 18 October 2019, archived at https://web.archive.org/web/20191125140351/https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions; car equivalent: calculated by dividing 533 million metric tons by the EPA estimate for annual emissions from a typical passenger vehicle (4.6 metric tons). EPA source: U.S. Environmental Protection Agency, *Greenhouse Gas Emissions from a Typical Passenger Vehicle,* accessed on 10 October 2019, archived at https://web.archive.org/web/20191125140508/https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle.

5. Fossil fuel use reduction: calculated by taking total estimated direct fossil fuel consumption in 2050 for transportation, industry and buildings sector (45.83 quads) and dividing by reductions in fossil fuel consumption in the buildings sector (10.23 quads); Source: Daniel Steinberg et. al, National Renewable Energy Laboratory, *Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization,* July 2017, archived at https://web.archive.org/web/20190926165518/https://www.nrel.gov/docs/fy17osti/68214.pdf.

1. Bruce Ho and Jackson Morris, Natural Resources Defense Council, RGGI Agrees to Cut Power Plant Pollution by Another 30%, archived at https://web.archive.org/web/20171127222309/https://www.nrdc.org/experts/bruce-ho/rggi-agrees-cut-powerplant-pollution-another-30, 27 November 2017.

6. Environmental Protection Agency, *Introduction to Indoor Air Quality,* accessed on 19 September 2019, archived at http://web.archive.org/web/20190730141940/https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality; Heart disease and carbon monoxide: ScienceDaily, "Carbon Monoxide May Cause Long-lasting Heart Damage,"29 January 2008, archived at http://web.archive.org/web/20150711154139/http://www.sciencedaily.com:80/releases/2008/01/080129125412.htm; Nitrogen dioxide and heart disease: Thomas Bourdrel et. al, "Cardiovascular effects of air pollution," *Archives of Cardiovascular Diseases,* 110(11):634-642, DOI: 10.1016, November 2017, archived at https://web.archive.org/web/20191125140646/https://www.sciencedirect.com/science/article/pii/S1875213617301304?via%3Dihub; Respiratory function and gas cooking: D. Jarvis et. al, "The association of respiratory symptoms and lung function with the use of gas for cooking. European Community Respiratory Health Survey," *European Respiratory Journal,* 11(3):651-658, March 1998, archived at http://web.archive.org/web/20190919192422/https://www.ncbi.nlm.nih.gov/pubmed/9596117; Formaldehyde and cancer: Environmental Protection Agency, *Facts About Formaldehyde,* accessed on 19 September 2019, archived at http://web.archive.org/web/20191014212947/https://www.epa.gov/formaldehyde/facts-about-formaldehyde.

7. U.S. Energy Information Administration, *2015 Residential Energy Consumption Survey Data,* 2017, archived at http://web.archive.org/web/20190630014648/https://www.eia.gov/consumption/residential/index.php.

8. U.S. Department of Energy, *Heat Pump Systems,* accessed on 11 October 2019, archived at http://web.archive.org/web/20191112070437/https://www.energy.gov/energysaver/heat-and-cool/heat-pump-systems.

9. Jacob Corvidae, Michael Gartman and Alisa Petersen, Rocky Mountain Institute, *The Economics of Zero-Energy Homes,* 2019, downloaded at https://rmi.org/insight/economics-of-zero-energy-homes/.

10. Heat pump efficiency: Comfort365, *Frequently Asked Questions,* accessed on 19 September 2019, archived at https://web.archive.org/web/20191125141341/http://wepowr.com/bouldercomfort365/faqs; Gas and oil efficiency: Stafor, COP - Coefficient of Performance, accessed on 19 September 2019, archived at http://web.archive.org/web/20181021075929/http://www.stafor.lv:80/gb/ion-heating-boilers/about-heaters/cop---coefficient-of-performance.

11. Neil Kolwey and Howard Geller, Southwest Energy Efficiency Project, *Benefits of Heat Pumps for Homes in the Southwest, June 2018, accessed at* http://www.swenergy.org/data/sites/1/media/documents/publications/documents/Heat%20pump%20study%20FINAL%202018-06-18.pdf.

12. Paul Hope, Consumer Reports, *Pros and Cons of Induction Cooktops and Ranges,* 13 June 2018, archived at http://web.archive.org/web/20190910074118/https://www.consumerreports.org/electric-induction-ranges/pros-and-cons-of-induction-cooktops-and-ranges.

13. Note: In many cases it can make sense to retrofit a building that uses an inefficient form of space heating – such as oil, propane of electric resistance. See Merrian Borgeson and Emily Levin, National Resource Defense Council, *Driving the Market for Heat Pumps in the Northeast,* 21 February 2018, archived at http://web.archive.org/web/20190723164707/https://www.nrdc.org/experts/merrian-borgeson/driving-market-heat-pumps-northeast.

14. Surveyed cities were Oakland, CA, Houston, TX, Providence, RI and Chicago, IL. Climate zones were from Building America. Climate zones: See Figure 1, Michael C. Baechler, Theresa L. Gilbride, Pam C. Cole, Marye G. Hefty, and Kathi Ruiz, Pacific Northwest National Laboratory, *Guide to Determining Climate Regions by County,* August 2015, accessed at https://www.energy.gov/sites/prod/files/2015/10/f27/ba_climate_region_guide_7.3.pdf; Cities: Sherri Billimoria, Leia Guccione, Mike Henchen and Leah Louis-Prescott, Rocky Mountain Institute, *The Economics of Electrifying Buildings,* 2018, downloaded at https://rmi.org/insight/the-economics-of-electrifying-buildings/.

15. Sherri Billimoria, Leia Guccione, Mike Henchen and Leah Louis-Prescott, Rocky Mountain Institute, *The Economics of Electrifying Buildings,* 2018, downloaded at https://rmi.org/insight/the-economics-of-electrifying-buildings/. Note: The Rocky Mountain institute ran analysis of various new construction and retrofit scenarios in Oakland, CA, Houston, TX, Providence, RI, and Chicago, IL.

16. Ibid.

17. Eric Wilson, Craig Christensen, Scott Horowitz, Joseph Robertson, and Jeff Maguire, National Renewable Energy Laboratory, *Energy Efficiency Potential in the U.S. Single-Family Housing Stock,* December 2017, accessed at https://www.nrel.gov/docs/fy18osti/68670.pdf.

18. Prices falling: Ran Fu, David Feldman, and Robert Margolis, National Renewable Energy Laboratory, *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018, November 2018; Lazard, Levelized Cost of Energy Analysis Version 12.0,* November 2018, archived at http://web.archive.org/web/20191013052337/https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf; John Weaver, "New record low solar power price? 2.175¢/kWh in Idaho," *PV Magazine,* 27 March 2019, archived at http://web.archive.org/web/20191112024014/https://pv-magazine-usa.com/2019/03/27/idaho-seeks-record-low-solar-power-price-2-175%c2%a2-kwh/.

19. Cole Latimer, "Too Much of a Good Thing: Solar Power Surge Is Flooding the Grid," *Sydney Morning Herald,* 6 June 2018, archived at http://web.archive.org/web/20180616065958/smh. com.au/business/the-economy/too-much-of-a-good-thingsolar-power-surge-is-flooding-the-grid-20180606-p4zjs7.html; Ivan Penn, "California Invested Heavily in Solar Power. Now There's So Much That Other States Are Sometimes Paid to Take It," *Los Angeles Times,* 22 June 2017, archived at http://web. archive.org/web/20181023024952/www.latimes.com/projects/ la-fi-electricity-solar/.

20. U.S. Department of Energy and Environmental Protection Agency, Energy Star, *Energy Star Home Tips,* accessed on 24 September 2019, archived at https://web.archive.org/web/20190809124344/https://www.energystar.gov/products/energy_star_home_tips.

21. Energy storage: Arina Anisie and Francisco Boshell, International Renewable Energy Agency, *Behind-the-Meter Batteries,* 2019, accessed at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_BTM_Batteries_2019.pdf?la=en&hash=86DF5CFBEDB71EB9A00A5E3680D72D6E346BD23A; Demand response: U.S. Department of Energy, *Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them,* February 2006, accessed at https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_Benefits_of_Demand_Response_in_Electricity_Markets_and_Recommendations_for_Achieving_Them_Report_to_Congress.pdf.

22. Elizabeth Noll and Meg Waltner, Natural Resources Defense Council, *Strong U.S. Energy Efficiency Standards: Decades of Using Energy Smarter,* 8 December 2014, archived at http://web.archive.org/web/20170215172028/nrdc.org/resources/. strong-us-energy-efficiency-standards-decades-using-energysmarter; see note 15.

23. Jeff Deason et al, U.S. Department of Energy, *Electrification of Buildings and Industry in the United States: Drivers, Barriers, Prospects, and Policy Approaches,* March 2018, archived at http://web.archive.org/web/20180516204646/http://ipu.msu.edu/wp-content/uploads/2018/04/LBNL-Electrification-of-Buildings-2018.pdf.

24. Ibid.

25. Ibid.

26. David Roberts, "Most American homes are still heated with fossil fuels. It's time to electrify," *Vox,* 2 July 2018, archived at https://web.archive.org/web/20191125144755/https://www.vox.com/energy-and-environment/2018/6/20/17474124/electrification-natural-gas-furnace-heat-pump.

27. Emily Deruy, "San Jose set to become largest U.S. city to enact natural gas ban," *The Mercury News,* 17 September 2019, archived at https://web.archive.org/web/20190917191322/https://www.mercurynews.com/2019/09/17/san-jose-could-become-largest-u-s-city-to-enact-natural-gas-ban/.

28. Zero Net Energy: Steven Winter Associates, National Institute for Building Sciences, *Net Zero Energy Buildings,* 2 August 2016, accessed at https://www.wbdg.org/resources/net-zero-energy-buildings; Zero Net Carbon: World Green Building Council, *What is Net Zero?* Accessed on 13 November 2019 at https://www.worldgbc.org/advancing-net-zero/what-net-zero.

29. Federal: U.S. Department of Energy, *Tax Incentives for Energy Efficiency Upgrades in Commercial Buildings,* accessed on 24 September 2019 at https://www.energy.gov/eere/buildings/tax-incentives-energy-efficiency-upgrades-commercial-buildings; State: Tonya Moreno, The Balance, *State Tax Breaks for Energy,* 25 August 2018, archived at http://web.archive.org/web/20190502094500/https://www.thebalance.com/state-tax-breaks-for-energy-3193337.

30. U.S. Department of Energy and North Carolina Clean Energy Technology Center, Database of State Incentives for Renewables and Efficiency, *Renewable Energy Property Tax Exemption – Indiana,* accessed on 9 October 2019 at https://programs.dsireusa.org/system/program/detail/54.

31. New York City: Yaniv Vardi, "Making Sense of Building Requirements and Opportunities in NYC," *Greentech Media,* 4 October 2017, accessed at https://www.greentechmedia.com/articles/read/making-sense-of-building-requirements-and-opportunities-in-nyc#gs.6htw1r; Austin: City of Austin, *Energy Conservation Audit and Disclosure Ordinance,* 31 May 2019, accessed at https://austinenergy.com/ae/energy-efficiency/ecad-ordinance/energy-conservation-audit-and-disclosure-ordinance.

32. See note 1.

33. Ibid.

34. Ibid.

35. Paolo Carnevale and Jeffrey D. Sachs, Sustainable Development Solutions Network, *Roadmap to 2050: A Manual for Nations to Decarbonize by Mid-Century,* September 2019, accessed at https://roadmap2050.report/static/files/roadmap-to-2050.pdf.

36. See note 7.

37. See note 15.

38. Heat pumps: Ibid; Induction stoves: Tyler Lynch and Cindy Bailen, Reviewed, *Induction Cooking–Here's Why You Should*

Make the Switch, 3 September 2019, accessed at https://www.reviewed.com/ovens/features/induction-101-better-cooking-through-science.

39. See note 1.

40. Sierra Club, *100% Commitments in Cities, Counties, & States,* accessed on 9 October 2019 at https://www.sierraclub.org/ready-for-100/commitments.

41. Intergovernmental Panel on Climate Change, *Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C approved by governments*, 8 October 2018, accessed at https://www.ipcc.ch/2018/10/08/summary-for-policymakers-of-ipcc-special-report-on-global-warming-of-1-5c-approved-by-governments/.

42. See note 4.

43. Environmental Protection Agency, *Greenhouse Gas Inventory Data Explorer,* accessed on 18 October 2019, archived at https://web.archive.org/web/20191125132550/https://cfpub.epa.gov/ghgdata/inventoryexplorer/

44. Ibid.

45. Emissions: Ramon Alvarez et. al, "Assessment of methane emissions from the U.S. oil and gas supply chain," *Science, 361(6398):186-188, DOI: 10.1126,* 13 July 2018, accessed at https://science.sciencemag.org/content/361/6398/186 (note: converted teragrams to US tons using the conversion multiplier of 1.102e+6); Methane potency: Environmental Defense Fund, *Methane: The other important greenhouse gas,* accessed on 19 September 2019, accessed at https://www.edf.org/climate/methane-other-important-greenhouse-gas.

46. Sid Perkins, Science, *Major U.S. Cities are Leaking Methane at Twice the Rate Previously Believed*, 19 July 2019, accessed at https://www.sciencemag.org/news/2019/07/major-us-cities-are-leaking-methane-twice-rate-previously-believed.

47. Ibid.

48. See note 5.

49. Chole Holden, "US Will Have 88 Gigawatts of Residential Demand Flexibility by 2023," *GreenTech Media,* 4 October 2018, accessed at https://www.greentechmedia.com/articles/read/88-gigawatts-by-2023-u-s-residential-flexibility-on-the-rise#gs.6z7osg.

50. See note 6.

51. Wendee Nicole, "Cooking Up Indoor Air Pollution: Emissions from Natural Gas Stoves," *Environmental Health Perspectives*, 122(1), DOI: 10.1289, 1 January 2014, archived at http://web.archive.org/web/20181122151646/https://ehp.niehs.nih.gov/doi/10.1289/ehp.122-a27.

52. International Gas Union, *Case Studies in Improving Urban Air Quality,* 2015, accessed at https://www.igu.org/sites/default/files/node-document-field_file/IGU_Urban_Air_Quality_Portrait.pdf

53. Cardiac and respiratory damage: Ibid; Neurological effects: The Lancet Neurology, "Air pollution and brain health: an emerging issue," *The Lancet,* February 2018, accessed at https://www.thelancet.com/action/showPdf?pii=S1474-4422%2817%2930462-3.

54. Federico Karagulian et. al, "Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level," *Atmospheric Environment, 120:1, pp 475-483,* November 2015, accessed at https://www.sciencedirect.com/science/article/pii/S1352231015303320.

55. National Institute of Environmental Health Sciences, *Hydraulic Fracturing & Health,* accessed on 9 October 2019 at https://www.niehs.nih.gov/health/topics/agents/fracking/index.cfm.

56. Union of Concerned Scientists, *The Hidden Costs of Fossil Fuels,* accessed on 9 October 2019 at https://www.ucsusa.org/clean-energy/coal-and-other-fossil-fuels/hidden-cost-of-fossils#24.

57. Coal dominates fossil fuels: U.S. Energy Information Agency, *Electricity explained: Electricity in the United States,*19 April 2019, accessed at https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php; Coal as one of the dirtiest fossil fuels: U.S. Energy Information Agency, *How much carbon dioxide is produced when different fuels are burned?* 4 June 2019, accessed at https://www.eia.gov/tools/faqs/faq.php?id=73&t=11.

58. See note 26.

59. David Roberts, "The key to tackling climate change: electrify everything," *Vox,* 27 October 2017, accessed at https://www.vox.com/2016/9/19/12938086/electrify-everything.

60. Mike Vredevoogd, Vredevoogd Heating and Cooling, *How Long Can You Expect Your Furnace to Last?* 10 December 2018.

61. See note 2.

62. U.S. Energy Information Administration, *Use of Energy Explained: Energy Use in Commercial Buildings,* 28 September 2018, archived at http://web.archive.org/web/20190925011236/https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php.

63. See note 7.

64. U.S. Energy Information Administration, *Space Heating and Water Heating Account for Nearly Two Thirds of U.S. Home Energy Use,* 7 November 2018, accessed at https://www.eia.gov/todayinenergy/detail.php?id=37433.

65. See note 7.

66. 5.5 quads total consumed for space and water heating, 4.5 quads from natural gas, propane, and fuel oil. See note 7.

67.Smarter House, *Types of Heating Systems,* accessed on 29 September 2019, archived at http://web.archive.org/web/20190223085158/https://smarterhouse.org/heating-systems/types-heating-systems/

68. Heating oil: U.S. Energy Information Administration, *Heating Oil Explained,* 1 February 2019, accessed at https://web.archive.org/web/20191125172252/https://www.eia.gov/energyexplained/heating-oil/use-of-heating-oil.php; Propane: See note 7.

69. See note 15.

70. Ibid.

71. Ibid.

72. Ibid.

73. See note 7.

74. Ibid.

75. See note 15.

76. Furnace lifespan: See note 60.

77. Cost savings: See note 15; Natural gas bans: Emily Deruy, "San Jose set to become largest U.S. city to enact natural gas ban," *The Mercury News,* 17 September 2019, archived at https://web.archive.org/web/20190917191322/https://www.mercurynews.com/2019/09/17/san-jose-could-become-largest-u-s-city-to-enact-natural-gas-ban/.

78.See note 7.

79. See note 64.

80. U.S. Energy Information Administration, *U.S. Households' Heating Equipment Choices are Diverse and Vary by Climate Region,* 6 April 2017, accessed at https://www.eia.gov/todayinenergy/detail.php?id=30672; Fuel oil: U.S. Energy Information Administration, *Heating Oil Explained,* 1 February 2019, accessed at https://web.archive.org/web/20191125172252/https://www.eia.gov/energyexplained/heating-oil/use-of-heating-oil.php.

81. U.S. Department of Energy, *Storage Water Heaters,* accessed on 29 September 2019 at https://www.energy.gov/energysaver/water-heating/storage-water-heaters.

82. U.S. Department of Energy, *Tankless or Demand-Type Water Heaters,* accessed on 29 September 2019 at https://www.energy.gov/energysaver/heat-and-cool/water-heating/tankless-or-demand-type-water-heaters.

83. Mary Farrell, "Tankless Water Heaters vs. Storage Tank Water Heaters," *Consumer Reports,* 25 January 2019, accessed at https://www.consumerreports.org/water-heaters/tankless-water-heaters-vs-storage-tank-water-heaters/; See note 7.

84. See note 7.

85. Building consumption: U.S. Energy Information Administration, *2012 Commercial Buildings Energy Consumption Survey, Table E1,* 17 May 2016, archived at https://web.archive.org/web/20191125145837/https://www.eia.gov/consumption/commercial/data/2012/index.php?view=consumption.

86. See note 62.

87. Ibid.

88. See note 85.

89. See note 15.

90. See note 23; Current installation numbers: See note 7.

91. See note 8; Vapor compression cycle: Heat Pump Association, *How do heat pumps work? The vapor compression cycle*, accessed on 31 October 2019 at https://www.heatpumps.org.uk/consumers/heat-pump-technical-information/the-vapour-compression-cycle/.

92. See note 8.

93. U.S. Department of Energy, *Geothermal Heat Pumps,* accessed on 31 October 2019 at https://www.energy.gov/eere/geothermal/geothermal-heat-pumps.

94. Higher costs: Energy Informative, *Saving Money With Geothermal Heat Pumps,* accessed on 31 October 209 at https://energyinformative.org/saving-money-with-geothermal-heat-pumps/.

95. See note 93.

96. U.S. Department of Energy, *Guide to Geothermal Heat Pumps,* February 2011, accessed at https://www.energy.gov/sites/prod/files/guide_to_geothermal_heat_pumps.pdf.

97. See note 10.

98. Stafor, *COP - Coefficient of Performance,* accessed on 29 September 2019 at https://www.stafor.lv/gb/ion-heating-boilers/about-heaters/cop---coefficient-of-performance.

99. U.S. Department of Energy, *Furnaces and Boilers,* accessed on 31 October 2019 at https://www.energy.gov/energysaver/home-heating-systems/furnaces-and-boilers.

100. See note 15.

101. See note 9.

102. Home Energy Saver, *Electric-Resistance Storage Water Heaters,* 1997, archived at http://web.archive.org/web/20100527211733/http://www.homeenergysaver.lbl.gov/consumer/help-popup/content/~consumer~nrr~water-heater-electric.

103. Jordann Browne, Nordic Heating and Cooling, *Do Air to Water Heat Pumps Provide Air Conditioning?* 4 May 2016, archived at https://web.archive.org/web/20190926194523/https://www.nordicghp.com/2016/05/do-air-to-water-heat-pumps-provide-air-conditioning/.

104. Martin Holladay, Green Building Advisor, *Heat-Pump Water Heaters Come of Age,* 13 April 2012, accessed at https://www.greenbuildingadvisor.com/article/heat-pump-water-heaters-come-of-age.

105. See note 11.

106. Jonathan Trout, Consumer Affairs, *Are Heat Pump Water Heaters Worth the Cost?* 29 August 2019, accessed at https://www.consumeraffairs.com/homeowners/heat-pump-water-heater-value.html#.

107. David Farnsworth, Jim Lazar, and Jessica Shipley, Regulatory Assistance Project, *Beneficial Electrification of Water Heating,* January 2019, accessed at https://www.raponline.org/wp-content/uploads/2019/01/rap-farnsworth-lazar-shipley-beneficial-electrification-water-heating-2019-january-final.pdf.

108. Fine Cooking, *How an Induction Cooktop Works,* accessed on 29 September 2019 at https://www.finecooking.com/article/how-an-induction-cooktop-works.

109. See note 12.

110. See note 51.

111. Wyoming Gas Company, *Why Natural Gas*, accessed on 29 September 2019 at https://www.wyogas.com/~wyogas/?page_id=242.

112. Aisha Abdelhamid, Clean Technica, *Solar Thermal Panels For Heating & Cooling,* 4 May 2015, accessed at https://cleantechnica.com/2015/05/04/solar-thermal-panels-heating-cooling/.

113. Hal Slater, American Council for an Energy-Efficient Economy, *Solar Hot Water: Which is better? PV + Heat Pump or Thermal,* 2013, accessed at https://aceee.org/files/pdf/conferences/hwf/2013/1C-slater.pdf.

114. See note 62.

115. Rob Thornton, International District Energy Association and Environmental and Energy Study Institute, *What is District Energy?* accessed on 21 October 2019 at https://www.eesi.org/topics/district-energy/description.

116. Sarah Busche, Devin Egan, Jim Lowe and Ken Smith, U.S. Department of Energy, *District Heating with Renewable Energy,* 20 November 2012, accessed at https://www.energy.gov/eere/about-us/community-renewable-energy-success-stories-webinar-district-heating-renewable-energy-text.

117. Rebecca Zarin Pass, Michael Wetter and Mary Ann Piette, Lawrence Berkeley National Laboratory, *A Tale of Three District Energy Systems: Metrics and Future Opportunities,* 2016, accessed at https://pdfs.semanticscholar.org/d86b/a8b76d56f11545437e5155a768303633f52e.pdf.

118. Building consumption: See note 85.

119. See note 62.

120. Martin Christoph Soini et. al, International Renewable Energy Agency, *Renewable Energy in District Heating and Cooling,* March 2017, accessed at https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/IRENA_REmap_DHC_Report_2017.pdf.

121. Trieu Mai et. al, National Renewable Energy Laboratory, *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States,* 2018, accessed at https://www.nrel.gov/docs/fy18osti/71500.pdf.

122. Justin Worland, "Why Your Office Is the Cause Of—and the Solution to—Climate Change," *Time,* 28 April 2018, accessed at https://time.com/4311258/climate-change-energy-efficient-buildings/.

123. City of New York, *OneNYC: Mayor de Blasio Announces Major New Steps to Dramatically Reduce NYC Buildings' Greenhouse Gas Emissions (press release),* 22 April 2016, accessed at https://www1.nyc.gov/office-of-the-mayor/news/386-16/onenyc-mayor-de-blasio-major-new-steps-dramatically-reduce-nyc-buildings-greenhouse.

124. U.S. Department of Energy, *LED Lighting,* accessed on 29 September 2019 at https://www.energy.gov/energysaver/save-electricity-and-fuel/lighting-choices-save-you-money/led-lighting.

125. Haniya Rae, "Here's Why New Appliances Use Less Energy," *Consumer Reports,* 21 April 2019, archived at http://web.archive.org/web/20190719090913/https://www.consumerreports.org/energy-efficiency/why-new-major-appliances-use-less-energy/.

126. Consumer Reports, *How to tame the energy hogs in your home,* 26 August 2015, archived at https://web.archive.org/web/20190926201914/https://www.consumerreports.org/cro/magazine/2015/08/tame-energy-hogs-in-your-home/index.htm.

127. Barbara Rook, "Behind-the-Meter Energy Storage Surges Ahead of Utility-Operated Batteries," *Solar Power World,* 26 February 2019, accessed at https://www.solarpowerworldonline.com/2019/02/behind-the-meter-energy-storage-surges-ahead-of-utility-operated-batteries/.

128. Fortress Power, *Grid-Tied Energy Storage,* accessed on 29 September 2019 at https://www.fortresspower.com/on-grid/.

129. See note 127.

130. Jennifer Delony, "Water Heaters as Energy Storage a Significant Potential Grid Resource, Brattle Group Says," *Renewable Energy World*, 17 February 2016, accessed at https://www.renewableenergyworld.com/2016/02/17/water-heaters-as-energy-storage-a-significant-potential-grid-resource-brattle-group-says/#gref.

131. Increased demand on grid: See note 121; Bi-directional power flow: National Renewables Energy Laboratory, *Electric Vehicle Grid Integration,* accessed on 21 October 2019 at https://www.nrel.gov/transportation/project-ev-grid-integration.html.

132. National Renewables Energy Laboratory, *Electric Vehicle Grid Integration,* accessed on 21 October 2019 at https://www.nrel.gov/transportation/project-ev-grid-integration.html.

133. Smart grids: Garrett Fitzgerald, Chris Nelder and James Newcomb, Rocky Mountain Institute, *Electric Vehicles as Distributed Energy Resources,* 2016, accessed at https://rmi.org/wp-content/uploads/2017/04/RMI_Electric_Vehicles_as_DERs_Final_V2.pdf; National Renewables Energy Laboratory, *Electric Vehicle Grid Integration,* accessed on 21 October 2019 at https://www.nrel.gov/transportation/project-ev-grid-integration.html.

134. U.S. Department of Energy, *Demand Response,* accessed on 11 October 2019 at https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/demand-response.

135. Jessie Mehrhoff, "Welcoming the Next Generation: Residential Demand Response 3.0," *Utility Dive,* 3 April 2019,

accessed at https://www.utilitydive.com/news/welcoming-the-next-generation-residential-demand-response-30/551947/; Environmental Defense Fund, *Saving Energy with Demand Response,* accessed on 24 September 2019 at https://www.edf.org/energy/saving-energy-demand-response.

136. Environmental Defense Fund, *Saving Energy with Demand Response,* accessed on 24 September 2019 at https://www.edf.org/energy/saving-energy-demand-response.

137. Peter Bronski et al, Rocky Mountain Institute, *The Economics of Demand Flexibility,* August 2015, available at https://rmi.org/wp-content/uploads/2017/05/RMI_Document_Repository_Public-Reprts_RMI-TheEconomicsofDemandFlexibilityFullReport.pdf.

138. See note 23.

139. David Roberts, "Utilities Fighting Against Rooftop Solar are Only Hastening Their Own Doom," *Vox,* 7 July 2017, accessed at https://www.vox.com/energy-and-environment/2017/7/7/15927250/utilities-rooftop-solar-batteries.

140. Energy Sage, "How Much Do Solar Panels Save?" accessed on 5 September 2018, archived http://web.archive.org/web/20180309141303/news.energysage.com/much-solarpanels-save/.

141. See note 9.

142. Kent Peterson, Paul Torcellini and Roger Grant, U.S. Department of Energy, *A Common Definition for Zero Energy Buildings,* September 2015, accessed at https://www.energy.gov/sites/prod/files/2015/09/f26/bto_common_definition_zero_energy_buildings_093015.pdf.

143. See note 9.

144. Zero Net Carbon Buildings: Architecture 2030, New Buildings Institute and Rocky Mountain Institute, *Zero Net Carbon Building,* 2018, accessed at https://architecture2030.org/wp-content/uploads/2018/10/ZNC_Building_Definition.pdf.

145. Ibid.

146. See note 15.

147. Ibid.

148. Ibid.

149. Ibid.

150. Ibid.

151. Percent of homes using fuel oil and propane: See note 7; Dirty fuel and expensive fuel: Ibid.

152. See note 15.

153. Ibid.

154. Rocky Mountain Institute: Ibid; Department of Energy: see note 17.

155. See note 15.

156. Compared to retrofitting with natural gas: Ibid.

157. See note 140.

158. Cara Goldenberg and Mark Dyson, Rocky Mountain Institute, *Pushing the Limit: How Demand Flexibility Can Grow the Market for Renewable Energy,* 14 February 2018, accessed at https://rmi.org/demand-flexibility-can-grow-market-renewable-energy/.

159. See note 23.

160. Heat pumps: See note 11; Stoves: Dave Hewitt, Northeast Energy Efficiency Partnerships, *Induction stoves: an option for new construction,* 31 July 2019, accessed at https://neep.org/blog/induction-stoves-option-new-construction.

161. Tyler Lynch and Cindy Bailen, Reviewed, *Induction Cooking–Here's Why You Should Make the Switch,* 3 September 2019, accessed at https://www.reviewed.com/ovens/features/induction-101-better-cooking-through-science.

162. See note 23.

163. Nate Adams, "Electrify Everything! A Practical Guide to Ditching Your Gas Meter," *GreenTech Media*, 8 May 2018, accessed at https://www.greentechmedia.com/articles/read/electrify-everything#gs.6z2em0.

164. See note 15.

165. Energy Sage, *Costs and Benefits of Air Source Heat Pump,* 27 September 2019, accessed at https://www.energysage.com/green-heating-and-cooling/air-source-heat-pumps/costs-and-benefits-air-source-heat-pumps/.

166. See note 23.

167. Ibid.

168. See note 17.

169. Asa S. Hopkins, Kenji Takahashi, Devi Glick and Melissa Whited, Synapse Energy Economies, *Decarbonization of Heating Energy Use in California Building,* October 2018, accessed at https://www.synapse-energy.com/sites/default/files/Decarbonization-Heating-CA-Buildings-17-092-1.pdf.

170. See note 23.

171. 85 percent: Jürgen Weiss, Michael Hagerty and María Castañer, The Brattle Group and WIRES, *The Coming Electrification of the North American Economy,* March 2019, archived at https://web.archive.org/web/20191125145136/https://wiresgroup.com/wp-content/uploads/2019/03/Electrification_BrattleReport_WIRES_FINAL_03062019.pdf

172. See note 121.

173. See note 171.

174. See note 121.

175. See note 171.

176. See note 26.

177. Dylan Sievers, Fresh Energy, *Fuel-Switching 101: moving towards an efficient and carbon-free future,* 24 July 2019, accessed at https://fresh-energy.org/fuel-switching-101-moving-towards-an-efficient-and-carbon-free-future/#targetText=How%20does%20efficient%20fuel%2Dswitching,through%20utility%2Df-unded%20conservation%20programs.

178. State House News Service, "State adjusts priorities in $2.8B energy program," *Sentinel & Enterprise,* 31 January 2019, accessed at https://www.sentinelandenterprise.com/2019/01/31/state-adjusts-priorities-in-28b-energy-program/.

179. Nichola Groom, "San Jose moves to ban natural gas in new residential buildings," *Reuters,* 17 September 2019, archived at http://web.archive.org/web/20190918141107/https://www.reuters.com/article/us-usa-naturalgas-sanjose/san-jose-moves-to-ban-natural-gas-in-new-residential-buildings-idUSKBN1W302J.

180. David Cohan, U.S. Department of Energy, *Energy Codes 101: What Are They and What is DOE's Role?* 31 May 2016, archived at http://web.archive.org/web/20190109173534/https://www.energy.gov/eere/buildings/articles/energy-codes-101-what-are-they-and-what-doe-s-role.

181. Building Codes Assistance Project, *Stretch and Reach Codes,* accessed on 31 October 2019 at http://bcapcodes.org/beyond-code-portal/stretch-and-reach-codes/#targetText=Stretch%20Codes,greater%20levels%20of%20energy%20efficiency.

182. Jennifer Thorne Amann, American Council for an Energy Efficient Economy, *Energy Codes for Ultra-Low-Energy Buildings: A Critical Pathway to Zero Net Energy Buildings,* 17 December 2014, accessed at https://aceee.org/research-report/a1403.

183. Steven Winter Associates, National Institute for Building Sciences, *Net Zero Energy Buildings,* 2 August 2016, accessed at https://www.wbdg.org/resources/net-zero-energy-buildings

184. World Green Building Council, *What is Net Zero?* accessed on 13 November 2019 at https://www.worldgbc.org/advancing-net-zero/what-net-zero

185. Charles Eley, Edward Mazria and Vincent Martinez, Architecture 2030, *Zero Code for California,* 29 August 2018, accessed at https://zero-code.org/wp-content/uploads/2018/09/ZERO-Code-California.pdf.

186. Jeff Daniels, "California Clears Final Hurdle for State's Landmark Solar Panel Mandate for New Homes," *CNBC,* 6 December 2018, accessed at https://www.cnbc.com/2018/12/06/california-clears-final-hurdle-for-state-solar-mandate-for-new-homes.html#targetText=A%20requirement%20for%20new%20homes,of%20the%20state's%20building%20code.&targetText=California%20is%20the%20first%20state,as%20multi%2Dfamily%20residential%20buildings.

187. See note 182.

188. Ibid.

189. Katie Gronendyke, State of Massachusetts, *Massachusetts' Nation-Leading Three-Year Energy Efficiency Plan Approved,* 30 January 2019, accessed at https://www.mass.gov/news/massachusetts-nation-leading-three-year-energy-efficiency-plan-approved-0.

190. See note 178.

191. Institute for Local Self-Reliance, *Energy Research Hot Spot: Inclusive Financing,* accessed on 20 November 2019 at https://ilsr.org/inclusive-financing/.

192. See note 29.

193. See note 30.

194. U.S. Department of Energy, *179D Commercial Buildings Energy-Efficiency Tax Deduction,* accessed on 27 September 2019 at https://www.energy.gov/eere/buildings/179d-commercial-buildings-energy-efficiency-tax-deduction.

195. David McGuire, Accounting Today, *Fixing the 179D Tax Deduction,* 19 March 2019, accessed at https://www.accountingtoday.com/opinion/fixing-the-179d-tax-deduction-for-energy-efficient-property.

196. Refundable tax credit: Tax Policy Center, *Briefing Book: What is the difference between refundable and nonrefundable tax credits?* accessed on 31 October 2019 at https://www.taxpolicycenter.org/briefing-book/what-difference-between-refundable-and-nonrefundable-credits.

197. New York City and Austin: See note 31; Berkley: City of Berkley, *Building Energy Saving Ordinance (BESO),* accessed on 24 September 2019 at https://www.cityofberkeley.info/BESO/.

198. City of Berkley, *Building Energy Saving Ordinance (BESO),* accessed on 24 September 2019 at https://www.cityofberkeley.info/BESO/; Buildings that already receive qualifying certifications for energy efficiency and sustainability, such as LEED, are except from the requirement. Source: City of Berkley, *Building Energy Saving, Chapter 19.81,* 14 July 2015, accessed at https://www.cityofberkeley.info/uploadedFiles/Planning_and_Development/Level_3_-_Energy_and_Sustainable_Development/BESOordinanceUpdated_20170329.pdf.

199. Ibid.

200. See note 31.

201. See note 163.

202. Erica Myers, Steven Puller, and Jeremy West, University of Berkley, University of Chicago and Massachusetts Institute of Technology, *Effects of Mandatory Energy Efficiency Disclosure in Housing Markets,* October 2019, accessed at http://e2e.haas.berkeley.edu/pdf/workingpapers/WP044.pdf.

203. Building Electrification Initiative, *Boulder, Colorado*, accessed on 9 October 2019 at https://www.beicities.org/cities/boulder.

204. See note 23.

205. Seventhwave, Minnesota Department of Commerce, *Improving Installation and Maintenance Practices for Minnesota Residential Furnaces, Air Conditioners and Heat Pumps,* 30 September 2016, accessed at http://mn.gov/commerce-stat/pdfs/card-improving-insullation.pdf.