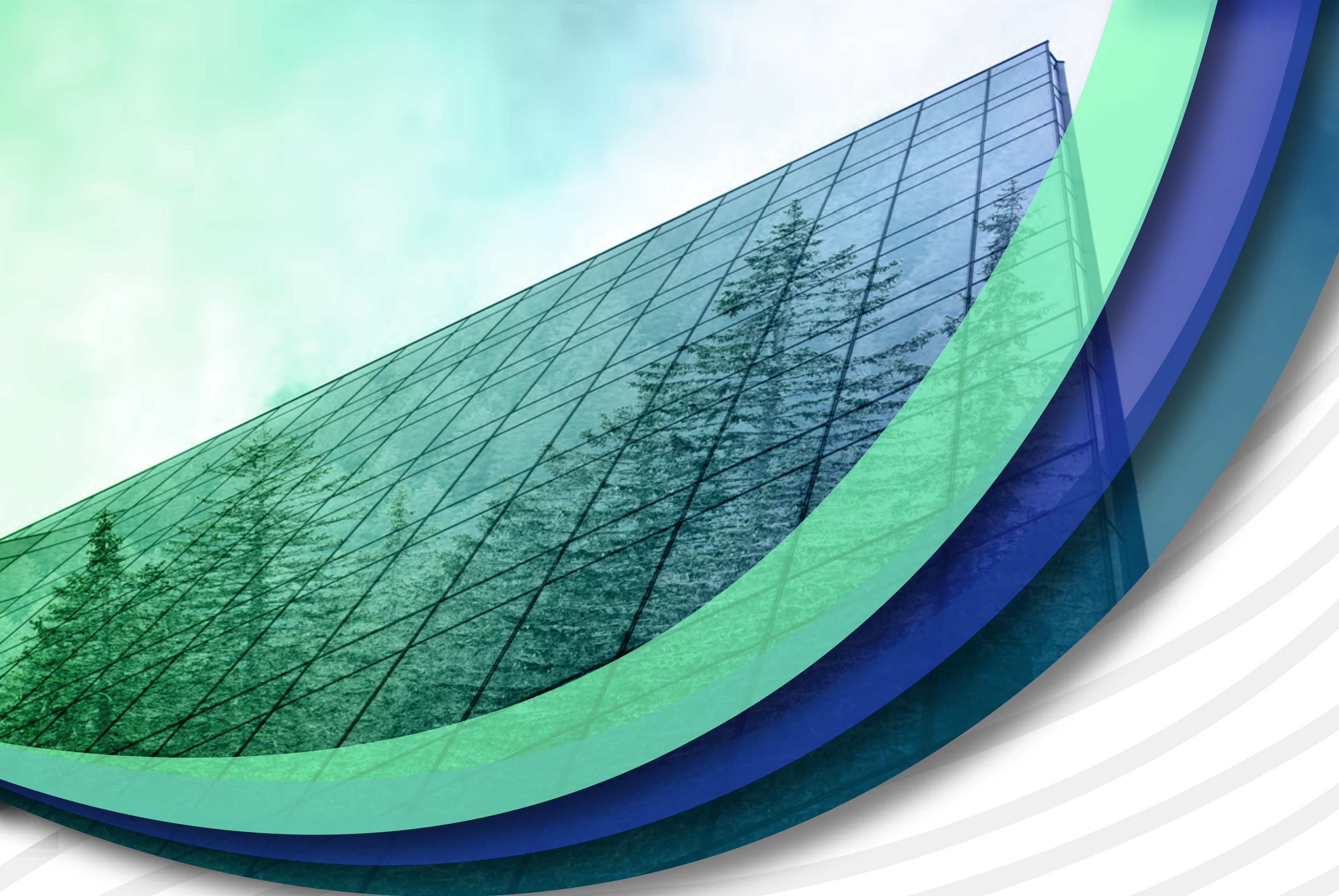

ELECTRIFYING SPACE HEATING IN EXISTING COMMERCIAL BUILDINGS: OPPORTUNITIES AND CHALLENGES

BY STEVEN NADEL AND CHRIS PERRY

RESEARCH REPORT
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Contents

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Executive Summary

KEY FINDINGS

- Our analyses find significant potential to save energy and reduce greenhouse gas emissions by electrifying existing commercial building space heating. The electrification opportunities we examined could reduce total commercial-sector site energy use in the portion of the commercial building stock we analyzed by about 37% and greenhouse gas emissions by about 44%.
- Our analysis of packaged systems, furnaces, boilers, and space heaters shows that about 27% of commercial floor space heated with fossil fuel systems can be electrified today with a simple payback of less than 10 years and without any rebates or carbon pricing. Financial incentives, carbon pricing and/or additional efficiency improvements to reduce building loads could improve payback for these buildings and would improve the economics of space-heating electrification for additional buildings.
- In a scenario that combines energy efficiency investments, electrification incentives, and carbon pricing, the share of floor area that can be electrified with a simple payback of less than 10 years increases to 60%, more than doubling the share meeting this threshold without a policy intervention.
- Buildings with the best paybacks are more likely to be located in the southern United States and the Pacific region, where space-heating needs are modest, and in building types across the United States that often have medium-to-high operating hours, such as health care, food, retail, and offices. These are general tendencies, and the economics of conversion will vary from site to site depending on energy use, costs, and other factors.
- Another opportunity is to convert centralized boiler/chiller systems to large chiller/heat pump systems. Some of these conversions have been completed, typically as part of major building renovations. However, the economics are highly site specific, and finding adequate exterior space to locate outdoor units can be a challenge for high-rise buildings.
- Given these realities, electrification of commercial space heating is likely to proceed slowly without policy support. Such support could include programs to promote energy efficiency, electrification incentives, pricing greenhouse gas emissions, mandatory building performance standards, research and development to reduce electrification costs, and encouraging/requiring bids for a heat pump when an existing heating system needs to be replaced.
- For some buildings with challenging economics, electrification may not be an all-or-nothing proposition. Meeting a substantial majority of the heating load with electricity and using a small amount of fuel backup could still result in major carbon and energy savings while also, in some cases, improving electrification economics.
- This analysis uses the present U.S. natural gas system as the base case. Given the need to decarbonize large portions of the U.S. economy to meet climate change goals, the alternative case should perhaps instead be gas-fired heat pumps fueled with renewable fuels. The costs of this alternative gas system are highly uncertain but are likely to be

substantially higher than the present gas system. As these costs become better known, a future analysis should compare electrification with this gas-based alternative.

Introduction

Interest in dramatically reducing greenhouse gas (GHG) emissions to limit the extent of climate change the world will face is growing. Efforts to date have often focused on no- and low-carbon electric generation, but many studies have found that to reduce GHG emissions by 80% or more relative to 2005 emissions, we also need to eliminate most emissions produced when fossil fuels are burned to heat buildings and water. A variety of studies have been conducted on electrification of the residential sector, but thus far no substantial study has focused on the commercial sector. This report is an initial effort to fill that gap.

Approach and Limitations

We used the Energy Information Administration's Commercial Building Energy Consumption Survey (CBECS) as the foundation of our analysis. CBECS includes detailed building characteristic and energy consumption information on a representative sample of 5,557 commercial buildings across the United States. The majority of these buildings are heated with fossil fuels. We conducted several analyses that look at converting existing natural gas space-heating systems to electric heat pumps when the existing systems need to be replaced. We considered three specific cases: (1) converting rooftop packaged systems that use natural gas to rooftop electric heat pumps; (2) converting gas furnaces to heat pump systems; and (3) converting gas boilers and space heaters to either ductless heat pumps (for small buildings) or variable refrigerant flow (VRF) heat pumps (for medium-size buildings). We also provide a detailed discussion of options to convert larger buildings using chillers and large boilers to various types of large heat pumps, but we did not have sufficient data to conduct an economic analysis.

These analyses are based on many assumptions. The estimates are generalized and do not account for individual building situations. As a result, our analyses should be considered approximate and not a substitute for analyses on individual buildings that can and should be done when making equipment replacement decisions. We discuss additional limitations in the body of the report.

Results

Our analyses find substantial potential for energy savings and GHG emissions reductions from electrification of commercial building space heating. Across our three analyses (rooftop units, furnaces, and space heaters), available site energy savings total 640 trillion Btu of energy and 36 million metric tonnes of carbon dioxide reductions. These savings are without regard to economics and thus can be considered the technical potential. These savings are 37% and 44%, respectively, of projected commercial-sector site energy use and energy-related emissions for the buildings covered by our three analyses.[1]

[1] Using *AEO* 2030 commercial building energy and emissions projections, including all buildings primarily heated by fossil fuels.

While substantial energy savings and emissions reductions opportunities are available, the economics of conversions are challenging for many buildings absent improved building and system efficiencies, reduced system costs, financial incentives, and/or a price on carbon emissions. Figure ES-1 provides an illustration. On the left is our medium-cost case, showing that about 27% of covered commercial building floor area can be converted to heat pumps with a simple payback period of 10 years or less at the time of equipment replacement without any financial incentives, carbon pricing, or additional efficiency improvements to reduce loads. On the right is a similar analysis that used the medium-cost case but also includes a 20% reduction in building energy use due to energy efficiency investments, a conversion incentive of $100 per ton of cooling capacity, and a carbon price of $50 per ton of carbon dioxide. With these program and policy interventions, the portion of floor area with a 10-year payback or less increases to 60%; these programs and policies can more than double the share of covered floor area with potentially attractive economics.

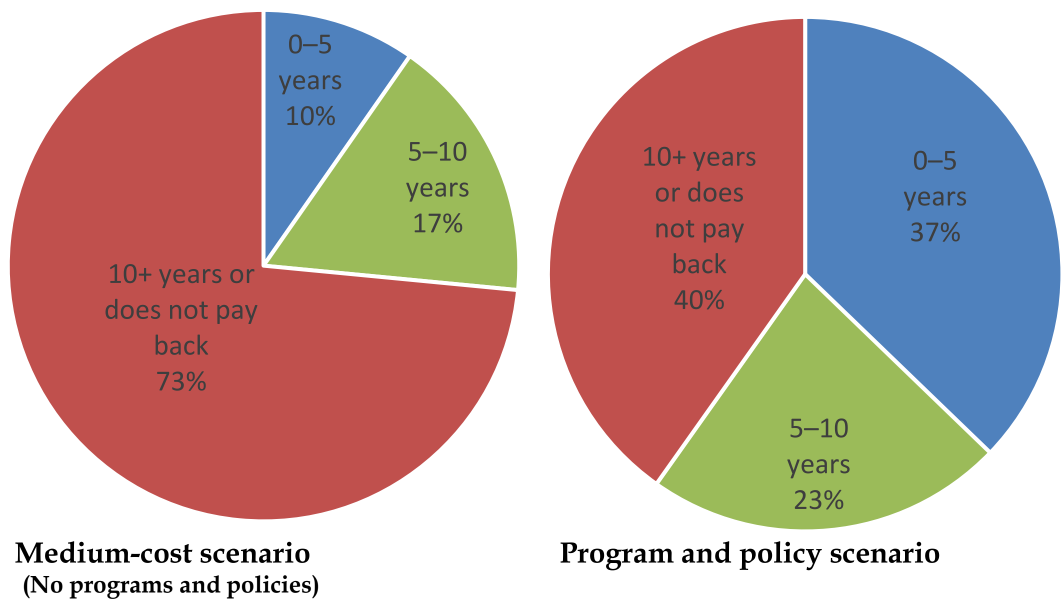

Figure ES-1. Distribution of the simple payback period by floor area for converting gas-fired rooftop systems, furnaces, space heaters, and small boilers to heat pumps when existing equipment needs to be replaced

Discussion and Conclusion

Our analyses find substantial potential for energy savings and GHG emissions reductions from electrification of commercial building space heating. However, the economics of conversions are challenging for many buildings absent improved system efficiencies, reduced system costs, financial incentives, and/or a price on carbon emissions.

The applications with better paybacks are a good place to start. These include much of the southern United States, the “hot” Mountain region, and the Pacific region, where space-heating needs are modest. Applications with better paybacks across the United States also include some specific building types, such as health care, malls and retail, food service, and offices. However, these are just tendencies, and the economics of conversion will vary from site to site depending on energy use, costs, and other factors.

Homes now using oil and propane have better electrification economics than homes using natural gas. We did not have sufficient data to conduct a similar analysis for commercial buildings. We also did not look at new construction; however, because work in the residential sector has found that new homes are often a good electrification opportunity, new commercial buildings are likely to be a good initial opportunity. In new construction, going all-electric can avoid the costs of providing gas service to and within the building.

Another large opportunity is converting centralized boiler/chiller systems. Some conversions have been done, typically as part of major building renovations. However, the economics are highly site specific, and finding adequate exterior space to locate outdoor units can be a challenge for high-rise buildings. More work is needed to examine conversion options and economics with more-detailed studies on a sample of buildings of different types and geographies.

This analysis is based on systems that are currently widely available and commonly used, such as rooftop heat pumps. Some promising opportunities that are on the horizon could improve conversion economics, such as using VRFs combined with high-efficiency dedicated outdoor air systems (DOASs) to replace rooftop units, and modular, packaged, and multi-pipe chiller/heat pump systems to replace large boilers. More work is needed to apply these new approaches to additional buildings and to study these projects to identify and refine best practices.

Given these realities, electrification of commercial space heating is likely to proceed slowly without policy support. While electrification would reduce GHG emissions and provide other societal benefits such as improved health (due to reduced emissions of multiple pollutants), significant upfront costs are involved. Policies and programs can help to realize the societal benefits while improving electrification economics for businesses. Electrification economics can be improved with incentives, a fee on GHG emissions, and packaging efficiency improvements with new heat pumps. Research and development are also important, as we should continue seeking ways to reduce the costs of electrification. Encouraging or even requiring building owners to get a heat pump bid whenever an existing fossil fuel heating system needs to be replaced could also be a useful step.

Even with policy support and incentives, electrifying space heating in some types of buildings, such as those with complex heating, ventilation, and air-conditioning (HVAC) systems or in cold climates, may still prove challenging. A variety of case studies presented in the body of this report indicate that, for many buildings, a viable strategy may be to electrify most of the load but continue to have a fuel-based backup for use on very cold days.

The natural gas industry might argue that instead of electrification, we can decarbonize using gas-fired heat pumps and what it calls "renewable gas." However, this alternative case will be substantially more expensive than the present U.S. gas system that has substantial GHG emissions. A future analysis should compare the economics and emissions of electrification versus a gas system using gas-fired heat pumps and so-called renewable gas.

Finally, we note that electrification of buildings will have profound impacts on utilities and the utility system; these impacts need to be factored into electrification strategies.

We are still early in the process of electrifying commercial building space heating. Initial projects are showing promising paths forward. We hope this analysis of opportunities and the need for policies will help accelerate our journey on this path.

Introduction

In 2019, the United States consumed 100.2 quadrillion British thermal units (Btu) of energy (quads), and energy-related carbon dioxide emissions totaled 5,138 million metric tons (tonnes). For both consumption and emissions, 31% were from direct use of fossil fuels in buildings and industry (EIA 2020d). Most climate scientists and many policymakers say that to avoid the most devastating impacts of climate change, the United States needs to reduce greenhouse gas (GHG) emissions by 80–100% (e.g., IPCC 2014, 2018). To achieve reductions on this scale, fossil fuel use in buildings and industry will need to be reduced substantially.[2]

One major strategy for reducing fossil fuel use in buildings and industry is electrification—replacing fossil fuel equipment with electric equipment, such as space- and water-heating heat pumps. As the electric grid becomes cleaner, particularly in states that set high renewable energy and clean energy goals, electrification can often reduce GHG emissions compared to onsite combustion of fossil fuels (e.g., see Nadel 2016, 2018).

To reduce GHG emissions by 80% or more, we will need multiple strategies. For example, in 2017, the Natural Resources Defense Council (NRDC) developed and documented a pathway for reducing U.S. GHG emissions by 80% by 2050. This pathway relied primarily on energy efficiency, renewable energy, and electrification, as illustrated in figure 1.

[2] The need to reduce fossil fuel use and emissions is likewise great in the transportation sector, which also offers substantial electrification opportunities. However, we limit the discussion in this paper to stationary uses of fossil fuels, and transportation is therefore not included.

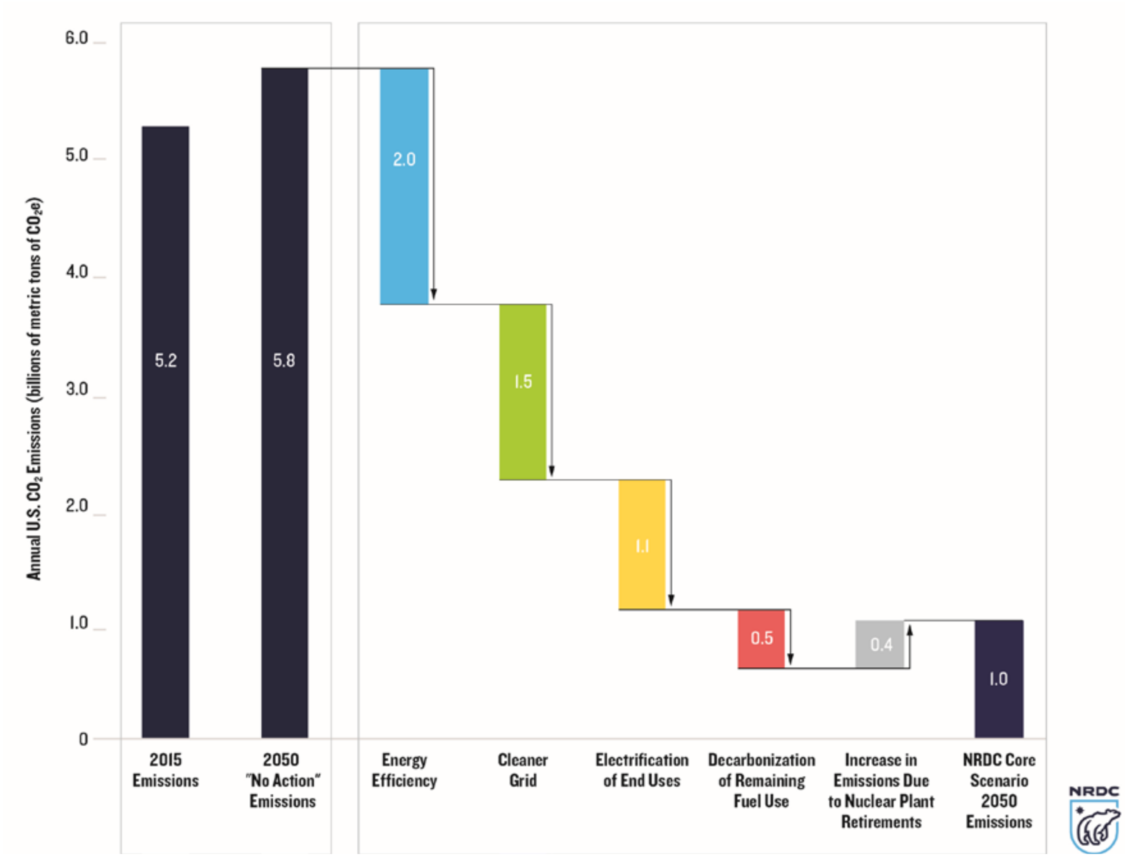

Figure 1. NRDC scenario for 2050 potential carbon dioxide emissions reductions in the United States. Electrification is in yellow. "Cleaner grid" means more use of no- and low-carbon electricity. "End uses" include transportation, buildings, and industrial energy uses. CO2e means carbon dioxide equivalent. In this chart, electrification includes transportation, buildings, and industry. *Source:* Gowrishankar and Levin 2017.

The natural gas industry argues that substantial amounts of what it calls "renewable natural gas" are available to decarbonize end uses without resorting to electrification. Such gas is derived from the digestion of biofeedstocks (often called "biogas") and can also include hydrogen and other fuels derived from renewable electricity. A recent study prepared for the American Gas Association Foundation (AGAF) found that biofeedstocks could produce about 1,500–3,750 trillion Btu of this gas by 2040 (low-resource and high-resource estimates) (ICF 2019).[3] This represents about 8–20% of projected 2040 U.S. natural gas use by the residential, commercial, and industrial sectors as estimated by the U.S. Energy Information Administration (EIA 2020a). NRDC (2020) reviewed the AGAF analysis and suggested reducing the estimate by nearly half to account for costs and total lifecycle GHG impacts. Even if the high-resource estimate is correct, decarbonization of fuel use will require much more than just this type of gas. Nadel (2020) suggests that, given these limitations, such fuel supplies should be dedicated primarily to applications that really need fuels, such as long-

[3] ICF also looked at opportunities to produce hydrogen fuel from renewable electricity, but we do not include this in our discussion because it is another way to use electricity. In addition, according to the ICF study, the cost of hydrogen from electricity is generally much higher than that of fuel from biofeedstocks.

distance trucking and aviation, high-temperature industrial applications, and supplemental heat on very cold days.

If renewable gas supplies are limited, then substantial electrification of space, water, and process heating will be needed to achieve decarbonization objectives of 80% or more. Gas may still have a role, but it will be limited, such as to provide backup heat on very cold days. In this context, we approach options for electrifying commercial buildings.

IMPLICATIONS OF ELECTRIFICATION STUDIES ON THE RESIDENTIAL AND INDUSTRIAL SECTORS FOR THE COMMERCIAL SECTOR

Residential electrification opportunities have been studied extensively by the American Council for an Energy-Efficient Economy (ACEEE) and others; these studies provide useful background and context for a commercial-sector analysis. Table 1 summarizes the average simple payback period for installing a heat pump when an existing oil or propane furnace, boiler, or water heater needs to be replaced. In general, payback periods are less than five years for replacing oil and propane furnaces for much of the United States, with the notable exception of the upper Midwest, where cold winters and low fuel prices make heat pump economics challenging.

Table 1. Average simple payback period for replacing residential oil and propane heating equipment with a heat pump at time of equipment replacement

	Average simple payback period (years)				
Comparison	US	West	Midwest	Northeast	Southeast
Oil furnace (83% AFUE) vs. HP (8.5 HSPF), includes AC savings	0.9	1.4	1.3 in MO; no savings in Upper MW	1.9	0.8
Propane furnace (80% AFUE) vs. HP (8.5 HSPF), includes AC savings	1.5	1.7	3.4 in MO; no savings in Upper MW	2.0	1.3
Oil boiler (86% AFUE) vs. ductless HP, without AC	4.4	7.3	18.8	6.2	5.1
Propane boiler (84% AFUE) vs. ductless HP, without AC	16.1	12.1	19.8	8.5	9.1
Std. oil water heater to HPWH (2.0 rated EF)	Immediate	Examined only at a national level			
Std. propane water heater to HPWH (2.0 rated EF)	3.9				

AC = air conditioning. AFUE = Annual Fuel Utilization Efficiency, a standard measure of the efficiency of fossil fuel heating systems. EF = Energy Factor, a measure of water heater efficiency. HP = heat pump. HPWH = heat pump water heater. HSPF = Heating Season Performance Factor, a seasonal measure of heat pump efficiency. MW = megawatt. Many homes with boilers do not have central air-conditioning. As a result, installing a heat pump in these homes does not involve air-conditioning savings. *Source:* Nadel 2018.

The Rocky Mountain Institute (Billimoria et al. 2018) examined residential electrification economics from a lifecycle cost perspective. It found that across four representative U.S. cities, lifecycle costs are generally lower for heat pumps than for gas furnaces for new construction and lower for heat pumps than fuel oil in existing homes (consistent with table

1). However, lifecycle costs are generally lower for natural gas furnaces than heat pumps in existing homes that already have air-conditioning. If a house does not have air-conditioning, installing a heat pump will generally be less expensive than installing both a furnace and an air conditioner. These findings are illustrated in figure 2.

These analyses suggest that in the commercial sector, the most promising electrification opportunities may also be in new construction, warm and temperate climates, and the small share of buildings currently using fuel oil or propane. The analysis we describe later in this paper tests some of these hypotheses (but not for new construction, as we look only at existing buildings in this report).

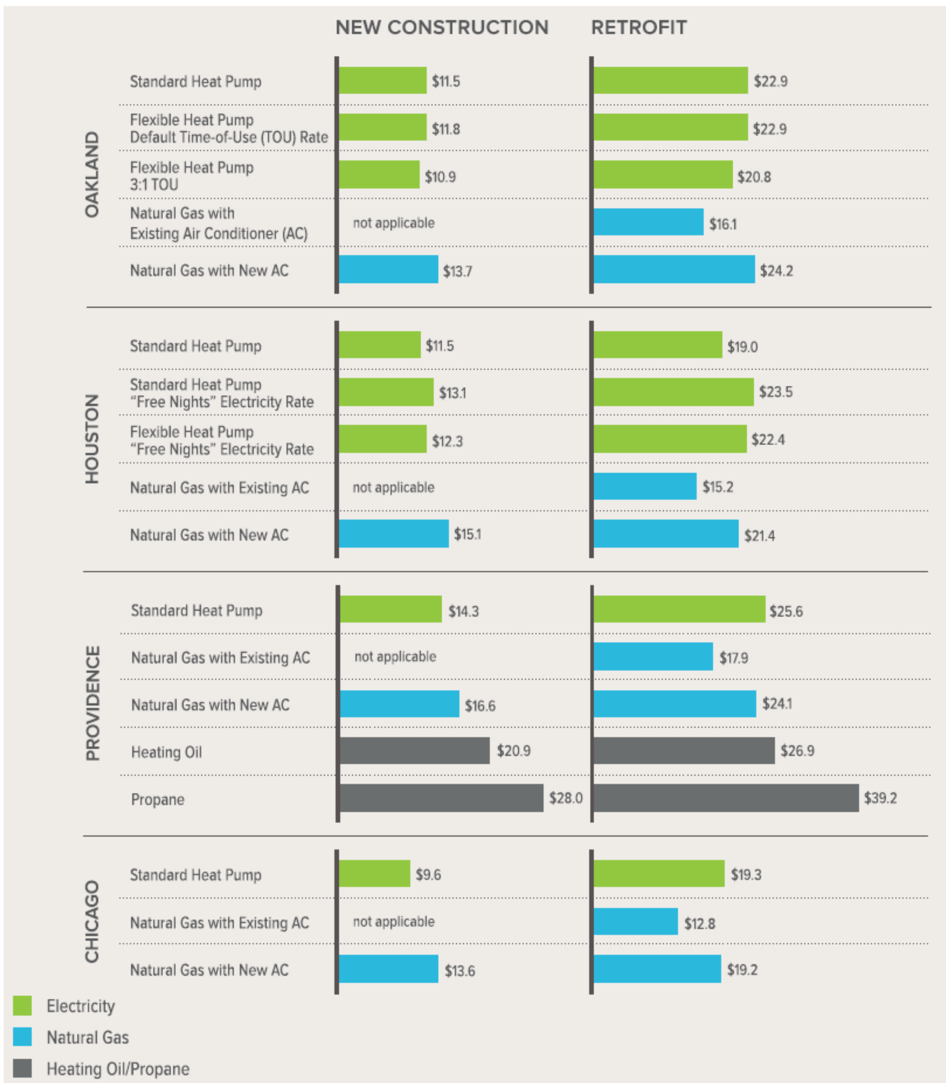

Figure 2. Comparison of 15-year net present value costs ($1,000) for space conditioning and water heating in five U.S. cities. *Source:* Billimoria et al. 2018.

The industrial sector is much more complicated than the residential sector. Electrification opportunities in the industrial sector will vary widely by facility and end use. Here too, past work can help inform a commercial-sector analysis. For example, Dennis (2016) looks at electro-technologies that have potential for rapid growth over the 2015–2020 period. His top 10 opportunities (in order of kilowatt-hour [kWh] growth) are cryogenics, direct arc melting, induction heating, resistance heating and melting, infrared processing, water supply reverse osmosis, induction melting, membrane processes, and electroslag/vacuum/plasma. He suggests that many of these are good opportunities because they can improve product quality and production productivity, address environmental requirements, or contribute to fast-growing industrial sectors. Some of these trends might apply in the commercial sector, particularly in fast-growing sectors (e.g., health care) or in applications where electrification might provide benefits beyond just heating (e.g., improved comfort).

PRIOR STUDIES ON ELECTRIFICATION IN THE COMMERCIAL SECTOR

Electrification opportunities in the commercial sector have been analyzed less than those in the residential and industrial sectors.

The National Renewable Energy Laboratory (NREL) has estimated potential electrification impacts in the commercial sector over the 2016–2050 period (Mai et al. 2018). However, this is an approximate analysis based on top-down estimates of electric technology potential penetration, illustrated in figure 3. NREL did not look at details by building type and construction, and it did not do any economic analysis.

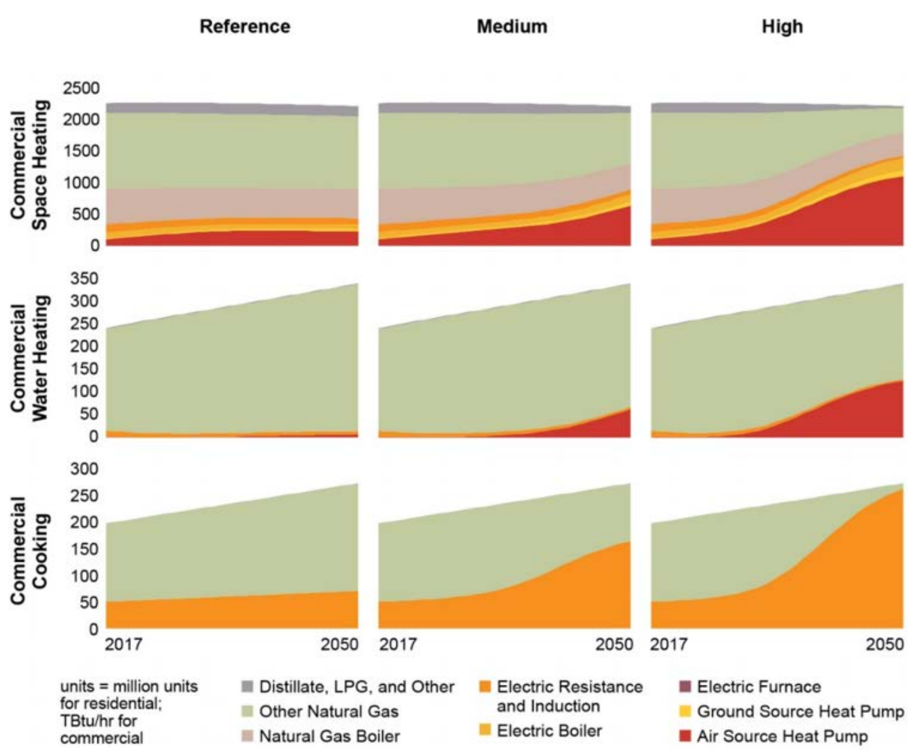

Figure 3. Projected energy use shares for U.S. commercial sector in NREL electrification scenarios.
Source: Mai et al. 2018.

A modeling study by researchers at Mississippi State University looked exclusively at medium-size offices, comparing standard efficiency rooftop units (RTU; systems that combine air-conditioning with gas burners for heating) with variable refrigerant flow (VRF) heat pumps in 16 U.S. cities. Their simulation results found that VRF systems would save around 15–42% and 18–33%, respectively, for heating, ventilation, and air-conditioning (HVAC) site and source energy uses compared with RTU systems. They also found that VRF systems have lower operating costs in all but the very coldest locations (Alaska and Montana). HVAC cost savings for VRF were higher on a percentage basis in hot and mild climates, due mainly to the differences in the need for heating (Kim et al. 2017). They did not look at relative capital costs.

We are not aware of any other studies that examine electrification opportunities in the U.S. commercial sector in any detail. Studies have been done on individual sites (we provide examples below), but there has been no systematic analysis across the commercial sector.

THIS STUDY

Given the scarcity of analysis on electrification opportunities in the commercial sector, we analyzed electrification energy savings and cost effectiveness for a wide range of actual buildings across all regions and all major commercial building and system types. We wanted to explore which HVAC systems, building types, and geographies provide the best electrification opportunities and which applications will be most challenging.

Specifically, we posed the following research questions:

- What are the most common types of space-heating systems currently used in commercial buildings that might provide large opportunities for electrification?
- What types of electric heating systems can replace common oil and gas equipment in specific applications?
- What is the approximate cost of each of these conversion options, and how much energy might they save?
- What are the overall economic and emissions impacts of conversion for different building types, systems, and geographies?
- What has been the experience to date in commercial buildings that have converted from fossil fuels to heat pumps?

Commercial-Sector Fossil Fuel Use

The first stage of our analysis examined data on fossil fuel energy use in the commercial sector. EIA provides consumption estimates by fuel and end use in its *Annual Energy Outlook* (*AEO*) (EIA 2020a). It estimates that in 2020, the commercial sector will use about 9.2 quadrillion Btu (“quads”) of energy onsite, plus an additional 8.8 quads offsite to generate electricity.[4] About half of the commercial building site energy is electricity, 39% natural gas, and the rest other fuels (figure 4).

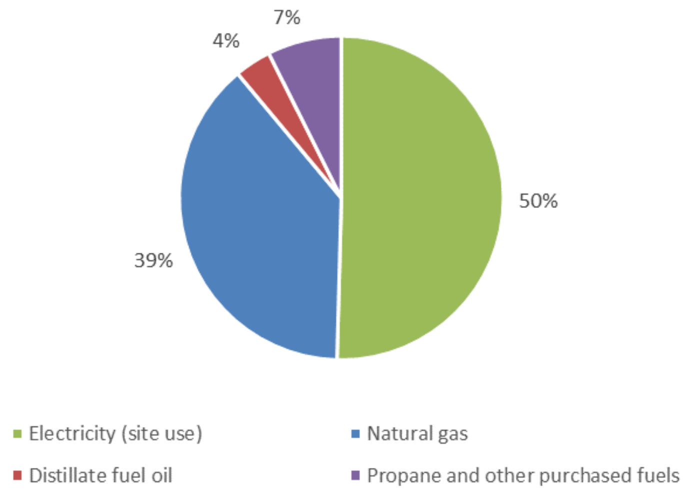

Figure 4. Estimated U.S. 2020 commercial-sector site energy use by fuel. *Source:* EIA 2020a.

The *AEO* also provides energy use estimates by end use (figure 5). Of total commercial-sector natural gas, oil, and other fuel energy use, 54% is for space heating, 16% for water heating, 9% for cooking, and the rest for other uses (includes cooling and miscellaneous uses, such as emergency generators, combined heat and power in commercial buildings, and manufacturing performed in commercial buildings). Because space heating is by far the largest end use for fuels, we selected it as the focus of this study.

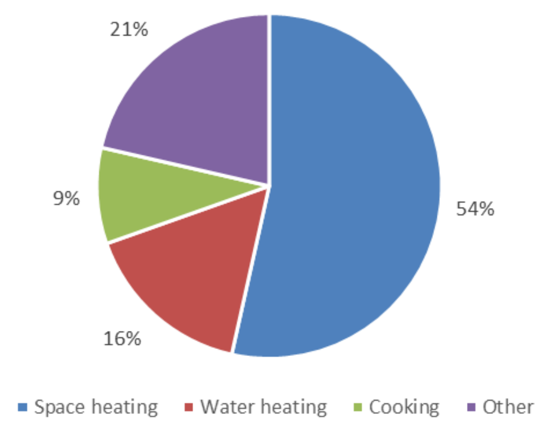

Figure 5. Estimated 2020 commercial-sector natural gas, oil, and other fuel use by end use. This energy use totals 4.6 quads. "Other" includes miscellaneous uses, such as emergency generators, combined heat and power in commercial buildings, and manufacturing in commercial buildings. *Source:* EIA 2020a.

[4] A quadrillion is a one followed by 15 zeros. By way of scale, the entire United States consumes about 100 quads per year.

More details on space-heating energy use are provided in the Commercial Building Energy Consumption Survey (CBECS). CBECS is prepared by EIA approximately every six years. It surveys a representative sample of commercial buildings across the United States, collecting and analyzing information on building characteristics and energy use. The most recent CBECS compiles data on 6,720 buildings from 2012 and was published in 2016 (EIA 2016b). The next CBECS will cover 2018, but the data analysis is still in process.

CBECS also provides further details on natural gas and fuel oil use. When we look at just natural gas and fuel oil in CBECS, space-heating use accounts for a higher proportion and "other" energy use a lower proportion than in the *AEO*. For natural gas, CBECS estimates 60% is used for space heating; for fuel oil, 69% is used for space heating. Combining these two fuels, 62% is used for space heating (figure 6).

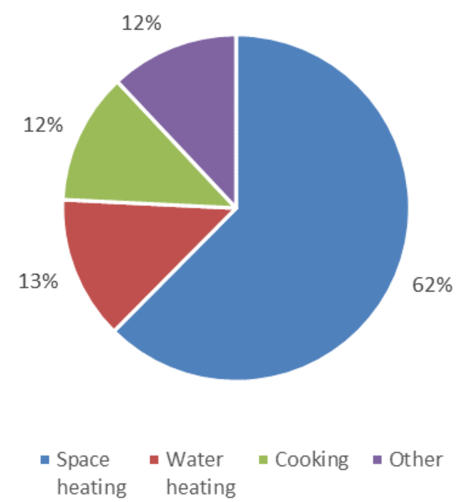

Figure 6. Commercial building natural gas and fuel oil use by end use, 2012. ***Source:*** **EIA 2016b.**

Looking just at space-heating energy use, CBECS reports that 62% of heated commercial building floor area uses natural gas for space heating, 61% uses electricity, 7% uses district heat, 5% uses fuel oil, 4% uses propane, and 1% uses "other." These total 141%, as some spaces use more than one heating source. If we normalize to 100%, 43% of space heating is by electricity, 56% by fossil fuels, and 1% by "other."

CBECS also provides data on the type of space-heating system installed. The most common system is a packaged heating system that is used to heat 61% of total commercial building floor area. Boilers are used to heat 28% of floor area, space heaters 26%, heat pumps 15%, and furnaces 7% (we describe these different types of systems in the next section). These total to more than 100% because some buildings use more than one type of space-heating system. Figure 7 shows the results of normalizing to 100%.

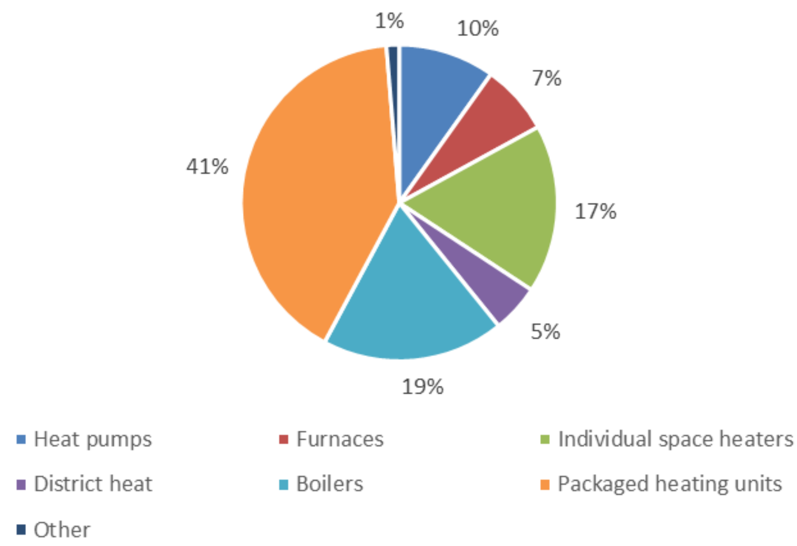

Figure 7. Total floor area by type of space-heating system. *Source:* EIA 2016b.

If we look only at buildings that use fossil fuels for heating, 44% of building floor area is in buildings using packaged heating systems, 38% in buildings using boilers, and 12–15% each in buildings using individual space heaters, furnaces, and district heating systems. Again, these figures total to more than 100% because some buildings use more than one type of heating system. Figure 8 shows the results of normalizing to 100%. On the basis of these data, we concentrated our research on packaged heating systems and boilers but also examined electric alternatives to furnaces and space heaters.

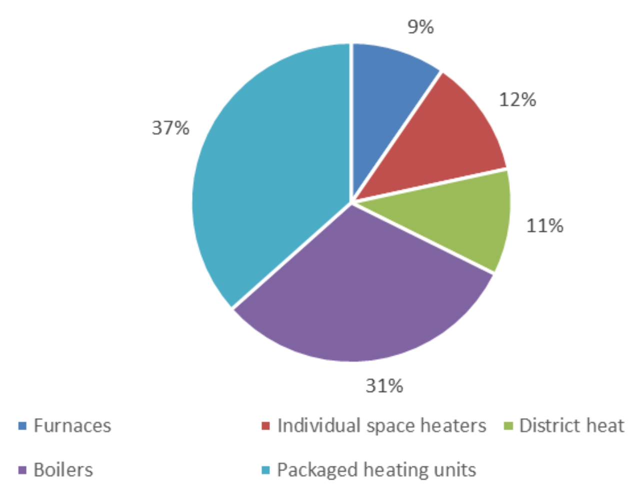

Figure 8. Total floor area using fossil fuels for space heating by type of space-heating system. *Source:* EIA 2016b.

CBECS also provides useful data on energy and fossil fuel use by building type and geography. Regarding building type, office buildings account for 20% of heated floor area, education for 15%, mercantile for 13%, and warehouses/storage for 12%. For buildings heated with fossil fuels, the percentages are generally similar except that education buildings are more likely to use fossil fuels (they account for 19% of floor area heated with fossil fuels) and mercantile buildings are less likely to use fossil fuels (accounting for 9% of floor area heated with fossil fuels).

Regarding geography, the Northeast accounts for 19% of heated floor area, the Midwest for 23%, the South for 38%, and the West for 21%. The regional percentages are generally similar for natural gas use except the Midwest is higher (28% of floor area heated with natural gas), and the South is lower (31%). For fuel oil and district heating, the Northeast accounts for 66% of floor area heated with oil and 33% of floor area heated with district heating, with other regions much lower. For propane, the Midwest is prominent (33% of floor area heated with propane). Another way to look at regional differences is to look at the most common heating fuels and system types in each region. These are summarized in table 2.

Table 2. Most common space-heating system type and space-heating fuel by region

Region	System type	Fuel
East North Central	Packaged heating systems	Natural gas
East South Central	Packaged heating systems	Electricity
Middle Atlantic	Boilers	Natural gas
Mountain (cold)	Packaged heating systems	Natural gas
Mountain (hot)	Packaged heating systems	Natural gas
New England	Packaged heating systems	Natural gas
Pacific	Packaged heating systems	Natural gas
South Atlantic	Packaged heating systems	Electricity
West North Central	Packaged heating systems	Natural gas
West South Central	Packaged heating systems	Electricity

Source: EIA 2016b

Heating-System Types

As discussed above, commercial buildings use many different types of heating systems. In this section, we briefly review the major system types in use today, and potential electric alternatives, to provide a foundation for subsequent sections of this report. The different fossil fuel systems are illustrated in figure 9.

PACKAGED HEATING SYSTEMS

A packaged unit is an all-in-one heating and cooling system for buildings that do not have a lot of room indoors for either a furnace and coil or an air handler. Packaged units contain all of their parts in one outdoor unit that sits either on either the roof or to the side of the building. In the commercial sector, RTUs are the most common type of packaged unit. Of these, the most common is often called a "gas-pack." It combines an air conditioner with a gas burner (figure 9). These can generally be replaced by rooftop heat pumps, although, as discussed in more detail later, in cold climates, heat pumps often require backup heat (fossil fuel or electric resistance) on very cold days.

BOILERS

Boilers heat water to create hot water or steam that is circulated through pipes to individual rooms where the heat is transferred to the air via radiators, fan coils, or baseboard units. Boilers are more difficult to replace with heat pumps, but they can sometimes be replaced with VRF, water-source, air-to-water, or multi-pipe heat pumps (all described below and in further detail in the Buildings with Central Boilers and Chillers section). A new heat pump can often serve much of the load over a winter, but some backup heat will be needed for very cold days in cold climates.

FURNACES

Furnaces heat air that circulates through ducts and into rooms. Furnaces are the most prevalent residential heating system and are also common in small commercial buildings, using either residential-size equipment or similar but somewhat larger versions. Fossil fuel systems can often be replaced with split ducted heat pumps, which have an outdoor unit and heat transfer coils in the ducts, very similar to most central air-conditioning systems.

SPACE HEATERS

Gas-fired space heaters are common in large open spaces such as garages and warehouses. They can sometimes be replaced with ductless or VRF systems (discussed below).

Figure 9. Illustration of different types of fossil fuel heating systems used in commercial buildings: gas-pack rooftop system (top left), boiler (top right), furnace (bottom left), and gas space heater (bottom right). *Sources:* Climate Control 2017; ASAP 2020; Dimare's Heating & Cooling Services 2020; eComfort 2020.

VRF AND OTHER DUCTLESS SYSTEMS

VRF systems heat or cool refrigerant that is piped to fan coils in different rooms of a building. VRF systems can be cooling-only or heat pump systems. Here we discuss only heat pumps. VRF heat pumps are a type of ductless heat pump, generally larger (in size and heating/cooling capacity) than typical "mini-split" ductless heat pumps commonly used in residences. A typical VRF system is illustrated in figure 10.

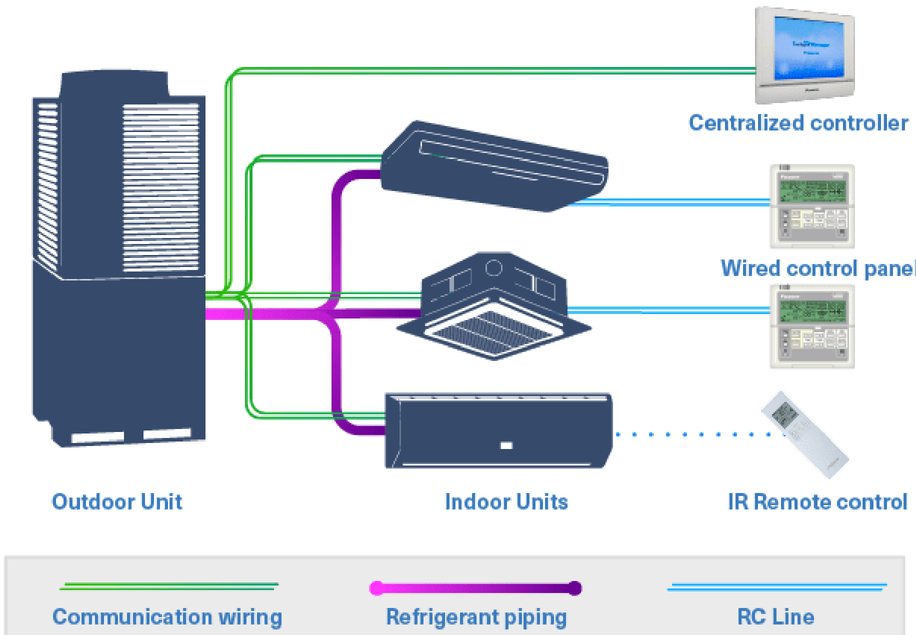

Figure 10. Schematic of a VRF system. *Source:* CoolAutomation 2019. IR = infrared. RC = a line used to link with the thermostat.

VRF systems are commonly air-source (they take heat out of the air), but they can also be water-source (e.g., linked with a water source such as a condenser loop, lake, well, or ground loop). They can also operate in heat recovery applications, where waste heat (air or water) is scavenged.

VRF systems have a variety of advantages and some limitations. VRF systems generally use variable-speed compressors and fans and can actively modulate refrigerant pressures and temperatures in response to outdoor and indoor conditions, making high efficiencies possible and improving heating capacity and efficiency at low outdoor temperatures (to 0°F and sometimes even lower). VRF systems generally take up less space than other system types; not only are the units themselves smaller, but they free up space that would typically be used by ducts, although some of this extra space may be needed for DOASs).

VRF systems can vary the flow of refrigerant from an outdoor unit to indoor units according to demand. This ability to control the amount of refrigerant that is provided to fan-coil units located throughout a building makes the VRF technology ideal for applications with varying loads or where zoning is required.[5] For example, CE News (Luke 2018) suggests that good applications include hotels, medical offices, educational facilities, and mixed-use facilities, where heating and cooling needs can vary widely among users. With many buildings less-fully occupied because more people are working from home because of the COVID-19 pandemic, more buildings may have varying heating and cooling loads.

[5] This advantage also applies to some other system types such as variable air volume RTU systems.

VRF systems often do not provide ventilation. The need for ventilation is generally based on an American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) standard on indoor air quality. In some small buildings with operable windows, the windows may provide adequate outdoor air, but in larger buildings and even many smaller buildings, a separate ventilation system is generally needed.[6] Because of concerns about transmission of COVID-19, the number of buildings needing DOASs with VRF systems is likely to increase. In addition, the heating and cooling capacity of VRF units is limited. For example, Daikin, perhaps the largest VRF manufacturer in terms of sales volume, has VRF systems as large as 14-ton cooling capacity for a single-module system and 34 tons for multi-module systems (Daikin 2020). These capacities are similar to RTUs, and as with RTUs, multiple systems can be used to serve larger buildings. However, because of the need for ventilation and limits on system size, VRF systems are used primarily in small- and medium-size buildings, though they can be used in larger buildings.

For smaller buildings, ductless heat pumps like those used in homes can sometimes be used. These systems are simpler and less expensive than VRF systems but, in appropriate applications, have many of the same advantages.

WATER-SOURCE HEAT PUMPS

Water-source heat pumps use water as a heat sink, such as waste warm water in an industrial plant. Similarly, they can be used to collect waste heat in a commercial building, such as reclaiming heat from water used to cool a chiller.

One of the more common applications in commercial buildings is a water-loop heat pump system. These systems work well in situations where a portion of a building needs heating and other portions need cooling. For example, in a large building in winter, the exterior portions of the building may need heating while the core of the building, which may have lots of internal loads and little heat loss, may need cooling. In this type of system, heat pumps located throughout the building are hooked up to a single water loop with the heat pumps in heating or cooling mode drawing off this loop. Thus, the core may cool the space and reject waste heat to the loop while the exterior portions of the building heat the space, drawing heat out of the loop. A pump circulates water in the loop throughout the building. This type of system is illustrated in figure 11.

[6] VRF systems are typically separate from ventilation systems, such as a DOAS. In certain cases, VRF systems can provide ventilation, such as indoor fan-coil units that are configured with some outside air ducted to the unit. However, the amount of outside air will be limited since VRF fan-coil units are not typically designed to remove humidity from raw outside air; therefore, a separate ventilation system is usually required (Duggin 2018).

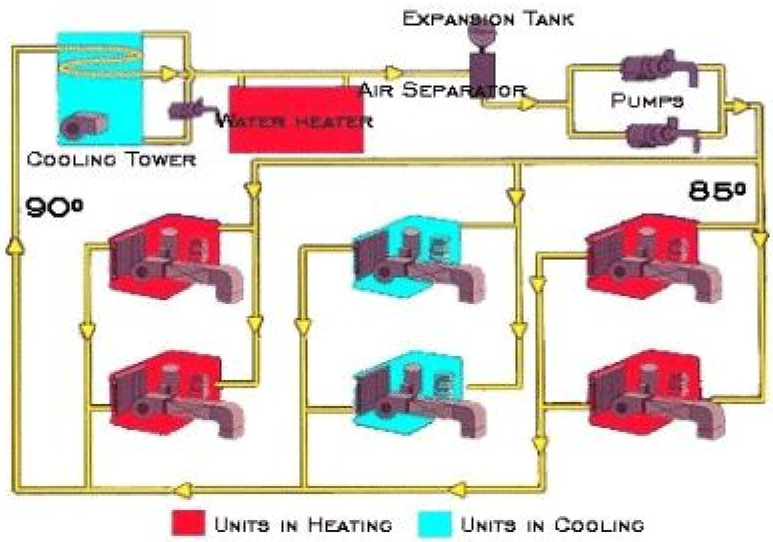

Figure 11. Schematic of a water-loop heat pump system. *Source:* Lansing Board of Water & Light 2020.

The benefit of this system is that it can be very efficient in buildings with appropriately matched heating and cooling loads for substantial portions of the year. Such systems often make the most sense in large buildings with large interior spaces. Matching loads can yield high overall efficiency. However, if loads are not reasonably matched, the substantial pumping energy and the need to heat or cool water in the loop to address unbalanced needs will decrease energy savings. These systems have several other advantages similar to those of air-source VRF systems; they lend themselves to zoning, and they require less space for equipment and ducts.[7] However, the disadvantages are that heat pumps, which require access for servicing, are located throughout the building, and increased electrical service (amps) is needed throughout the building. Also, in cold climates, an additional source of heat may be needed for very cold days (Alabama Power 2020). This backup can be an electric resistance or fossil fuel boiler.

AIR-TO-WATER HEAT PUMPS

Some heat pumps pull heat from ambient air to heat water that is then be circulated through radiators, baseboard units, or radiant panels. Such systems can be used to replace boilers. For example, Siegenthaler (2018) discusses one such system.

MODULAR, PACKAGED, AND MULTI-PIPE HEAT PUMPS

A variety of larger heat pump systems can sometimes be used to replace boilers. We discuss these below in the Buildings with Central Boilers and Chillers section.

[7] Water-source VRF heat pumps can also be used in a water-loop system.

GROUND-SOURCE SYSTEMS

Ground-source heat pumps use the moderate temperature of the ground as a heat sink. In the winter, the ground is warmer than the outside air, and in the summer the reverse is true. Using these more moderate temperature sinks substantially improves energy efficiency. Ground-source heat pumps link to the ground via heat exchangers in the ground, which can be vertical or horizonal. This ground link and a typical system are illustrated in figure 12. Commercial systems commonly use vertical heat exchangers, known as vertical boreholes or a bore field, as illustrated in figure 12.

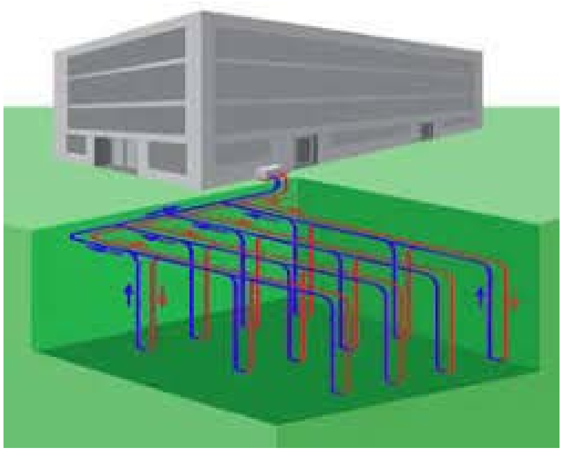


Figure 12. Schematic of a ground-source heat pump system on the left, actual heat pumps on the right. ***Sources:*** **IGSHPA 2009 and TLJ Engineering Consultants 2020.**

In larger buildings, the number of vertical boreholes required can increase quickly, and larger thermal piles are often used to increase the surface area and physical output of each hole required. At a recent project at a large campus, thermal piles were placed around structural piles required for the building, making the system first-cost neutral (Peters 2017).

Ground-source systems often use heat pumps designed for ground-source applications, but VRFs, water-loop heat pumps, and multi-pipe systems can all be linked to ground-source loops (we discuss some examples in the section on replacing boilers and chillers).

The main advantage of ground-source heat pumps is their high efficiency. For example, on the basis of field monitoring of a system installed at the student center at the University of Stockholm, Spitler and Gehlina (2019) report a seasonal coefficient of performance (COP) of about 3.7 for a ground-source heat pump system. By comparison, a typical seasonal COP for an air-source heat pump in northern Europe might be 2.5 (GreenMatch 2020). In addition, because the ground is the heat source, ground-source heat pumps work better at low temperatures, and thus less backup heat is needed than with air-source heat pumps.

The prime disadvantage of ground-source systems is cost; the cost of the ground link is often substantial. In addition, such links are possible only where there is sufficient open ground near a building and when soil and geology considerations are suitable (e.g., it is difficult to deploy drilling equipment in densely populated areas; it is also very challenging to drill through solid bedrock).

Analysis Methodology for this Study

For this study, we used individual building data in CBECS to assess the energy use, economics, and emissions of converting, at the time of failure, building space-heating systems from fossil fuels to an appropriate heat pump system.[8] CBECS covers all commercial building types for the entire United States and notes the Census region in which each building is located, allowing us to look at regional and national trends. Census regions are illustrated in figure 13. CBECS does not include multifamily buildings, so they buildings are not included in our analysis.[9] In the following paragraphs, we briefly discuss our approach; additional details are in the Appendix. Table 3 summarizes specific system types for our different analyses.

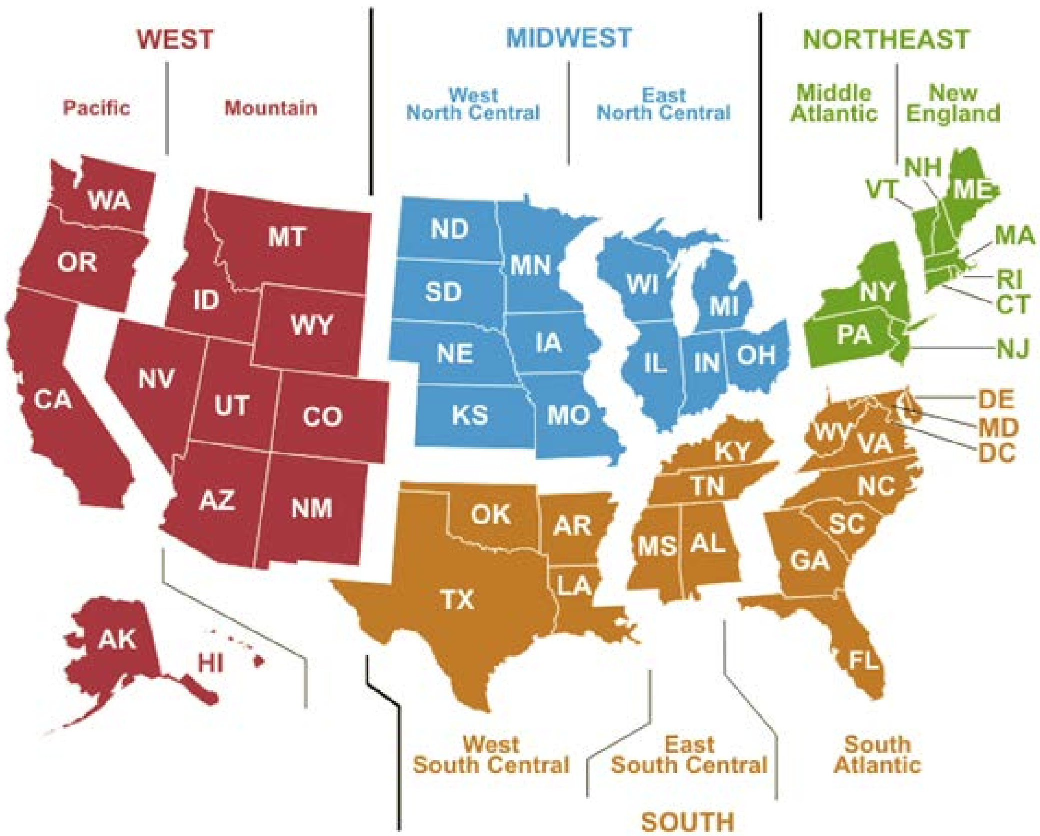

Figure 13. Census regions. For packaged systems, we analyzed the costs and impacts of converting to a packaged heat pump. For furnaces, we analyzed conversion to a split-system or packaged heat pump. For boilers and space-heating systems, we looked at installing ductless "mini-split" heat pumps or VRF systems instead. *Source:* EIA 2020b.

[8] Electrification can also be done with electric resistance heat, but these systems are generally substantially less efficient than heat pumps. For this reason, we examine only heat pumps.

[9] Multifamily buildings are instead included in EIA's Residential Energy Consumption Survey (RECS).

Table 3. Electrification options examined

Present fossil-based system type	Fossil fuel replacement	Electric heat pump alterative
RTU with natural gas	System of same type as present system but meeting current efficiency standards	Rooftop heat pump
Natural gas furnace + central air-conditioning	System of same type as present system but meeting current efficiency standards	Split or packaged heat pump to replace present furnace and air-conditioning system
Small/medium gas or oil boiler or space heater + central, room, or no air-conditioning	System of same type as present system but meeting current efficiency standards	Ductless or VRF heat pump
Large central gas or oil boiler + central chiller system	System of same type as present system but meeting current efficiency standards	Central chiller/heat pump

We conducted analyses on the first three system types; for the fourth system type we just discuss options.

Our analysis for each equipment type begins with actual 2012 energy use for space heating, space cooling, and ventilation. We made assumptions about the efficiency of each building's 2012 heating and cooling system to convert their consumption to heating and cooling demand. We then made assumptions about heat pump seasonal efficiency to convert this heating and cooling demand to electricity consumption. Our heat pump efficiencies are based on high-efficiency equipment from several major manufacturers and winter temperatures at each building site (e.g., efficiencies are much higher in Houston than in Minneapolis). Further details are provided in the Appendix. We assume that new fossil fuel equipment to replace existing equipment (the middle column of table 3) meets 2020 minimum efficiency standards and thus is generally more efficient than the equipment being replaced. Our efficiency assumptions vary by equipment type. We then adjusted this consumption for a typical year because 2012 had a warmer-than-average heating season. For this adjustment, we used heating and cooling degree day data for 2006–2015 obtained from the U.S. Environmental Protection Agency (EPA) (EPA 2016). This analysis tells us whether and how much energy heat pumps save on average (calculated by region and building type).

We then conducted an economic analysis from the building owner perspective, comparing the up-front capital and operating costs of a high-efficiency heat pump system with a replacement fossil fuel system. Our analysis sized the heat pumps for site-specific winter design temperatures.[10] We developed high, low, and midpoint cost estimates for the installed cost of systems. We conducted our primary analysis (the medium-cost scenario) with the midpoint costs, used the low and high costs for the sensitivity analysis. We based energy costs on actual electricity and fuel costs paid by each building in 2012 as noted in CBECS (which captures local and building-specific factors). We then adjusted for energy price trends from 2012 to projected 2030 prices, per the EIA *AEO* reference case. We used

[10] We used temperatures that are reached only 0.4% of the hours in the average winter (the "99.6% design temperature").

2030 because this new equipment will typically operate from 2020 until well into the 2030s. Using these capital and energy costs, we calculated lifecycle costs (over the estimated lifetime of each class of heat pump) and simple payback for each building, then averaged or calculated a median for each region and building type. Where possible, we presented findings calculated using CBECS weighting factors (which estimate the prevalence of the building type in the United States); the exception is that when we present median values, these are not weighted because of challenges applying the weighting factors to the calculation of medians.

Our environmental analysis looks at the GHG emissions impacts of electrification in each building. For fuels, we used standard EIA emissions factors. For electricity, we assigned an emissions factor for each building based on average 2030 projected emissions per kWh in each region, per the EIA *AEO* reference case. We included a price on carbon emissions in a sensitivity analysis but not in the main analysis.

Limitations

This analysis is based on many assumptions, as described above and in the Appendix. These assumptions are generalized estimates and do not account for individual building situations. For example, equipment installation costs will vary from site to site. We also account for potential future changes in system efficiencies and costs in only a rudimentary way using our "low cost" scenario; as technology develops and sales volumes increase, we hope that efficiency ratings will improve and costs decline per unit of efficiency. Our analysis is based on a single type of replacement system for each system type when, in fact, multiple options are available. For some buildings, a different system type might be a better choice than the systems we modeled. We also modeled full-building electrification without a backup fossil fuel system; for some buildings, as shown by several case studies we discuss below, displacing most but not all of the fossil fuel heating load may make the most sense. Furthermore, our analysis is based on average cost per kWh of electricity and does not account for the specifics of each customer's rate; because we use an average annual rate, our analysis does not account for the specific impacts of time-of-use and seasonal rates and demand charges. As a result, our analysis should be considered approximate and not a substitute for analyses on individual buildings that can and should be conducted when making equipment replacement decisions.

Likewise, our sensitivity analyses on carbon pricing and utility incentives use a single set of assumptions. Many other options are possible that we have not analyzed.

Our analysis is based on fully converting buildings to electricity. As we discuss later, supplying most of a building's heat with heat pumps while using a backup source of heat on very cold days may make sense in some or even many applications. We did not include this option in our analysis to keep the scope manageable.

This analysis uses the present natural gas system as the base case. Given the need to decarbonize large portions of the U.S. economy to meet climate change goals, the alternative case in future years should perhaps instead be gas-fired heat pumps fueled with renewable fuels. This alternative case would be substantially more expensive than the present system.

We did not examine this alternative to keep our scope manageable, but also because the costs of this alternative system are highly uncertain.

Finally, our analysis is based only on existing buildings. An analysis on new commercial buildings would be very useful because, as discussed above, residential-sector analyses show better economics in new construction than in existing buildings.

Results by System Type

In this section, we discuss the results of our analysis of buildings that are presently heated with packaged systems, furnaces, or space heaters. For each system type, we conducted a detailed building-by-building analysis. For buildings with large boilers, the engineering and economics of electrification are highly site specific. We discuss some of the considerations involved and some examples below.

PACKAGED UNIT CONVERSION TO PACKAGED HEAT PUMP

Our analysis of packaged systems was based on buildings in CBECS that now use gas packaged systems for space heating (CBECS does not provide propane consumption data and very few RTUs have oil heat, so we did not analyze these fuels). In total, CBECS has detailed data on 1,327 buildings served primarily by natural gas packaged systems, which is 20% of the total CBECS sample. Our packaged system analysis compared a rooftop gas-pack unit meeting the minimum efficiency standards DOE set in 2016 (12.7 IEER[11], 80% thermal efficiency) with a high-efficiency heat pump (composite of units offered by four major manufacturers (16.33 IEER, 2.43 COP at 17˚ F[12])).

Energy Savings

In all regions, high-efficiency heat pumps reduce site energy use. Total savings potential is highest in populous and cold regions because energy use is highest there. In addition to heating savings, there are ventilation energy use reductions (the high-efficiency heat pumps all have variable-speed or multiple-speed ventilation fans, while baseline units were assumed to be single speed) and cooling savings (high-efficiency heat pumps have higher cooling season efficiencies than standard RTUs). Annual savings by region are illustrated in figure 14. These calculations assume that all existing RTUs are replaced by heat pumps when the existing systems need replacement; thus, it will take just over 20 years to fully achieve these savings. A breakdown of RTU savings among air-conditioning, heating, and ventilation is provided in the Appendix.

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[11] IEER stands for Integrated Energy Efficiency Ratio, which is an efficiency measurement based on the weighted average of EER ratings at four load capacities – 100%, 75%, 50%, and 25%. EER stands for Energy Efficiency Ratio, the efficiency rating of an air conditioner or heat pump based on a test procedure run at the unit's 100% load capacity. Thermal efficiency is the energy efficiency measurement of the gas heating portion of the unit.

[12] COP stands for Coefficient of Performance, the ratio of heating provided to energy consumed. Manufacturers publish COP ratings at 17˚F and 47˚F.

Figure 14. Total energy savings by region from installing a rooftop heat pump when an existing packaged system with gas heat needs to be replaced

Total energy savings by building type are highest for strip shopping malls and offices—building types that are numerous and have substantial energy use (figure 15).

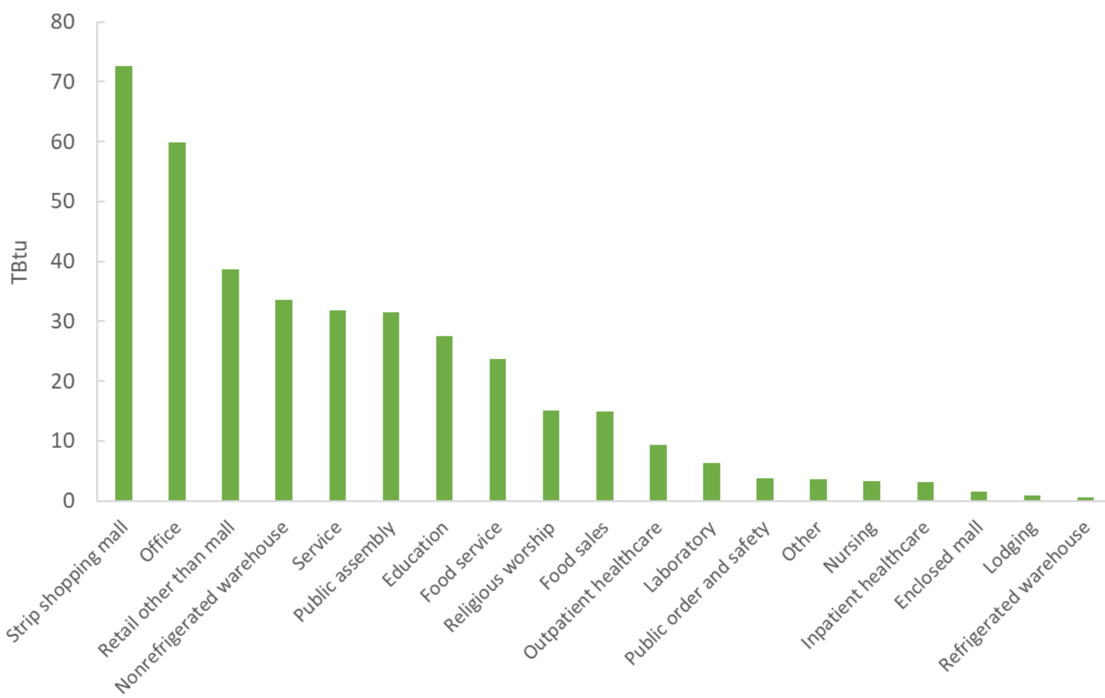

Figure 15. Total energy savings by building type from installing a rooftop heat pump when an existing packaged system with gas heat needs to be replaced

Economics

We found that the economics of high-efficiency packaged heat pumps vary widely by region. While energy savings are highest in cold regions, the economics of converting to a high-efficiency heat pump are much better in warm regions. In warmer regions, the median simple payback, in our midpoint price scenario, is approximately 10 years.[13] In cold regions, the median simple payback is longer than the approximately 22-year life of the equipment; therefore, the electrification option is not cost effective for the median building without incentives or other inducements (figure 16). This is also shown in our analysis on median lifecycle savings (figure 17). When simple payback periods exceed about 13 years, lifecycle costs are often negative at the discount rate we used (5% real).

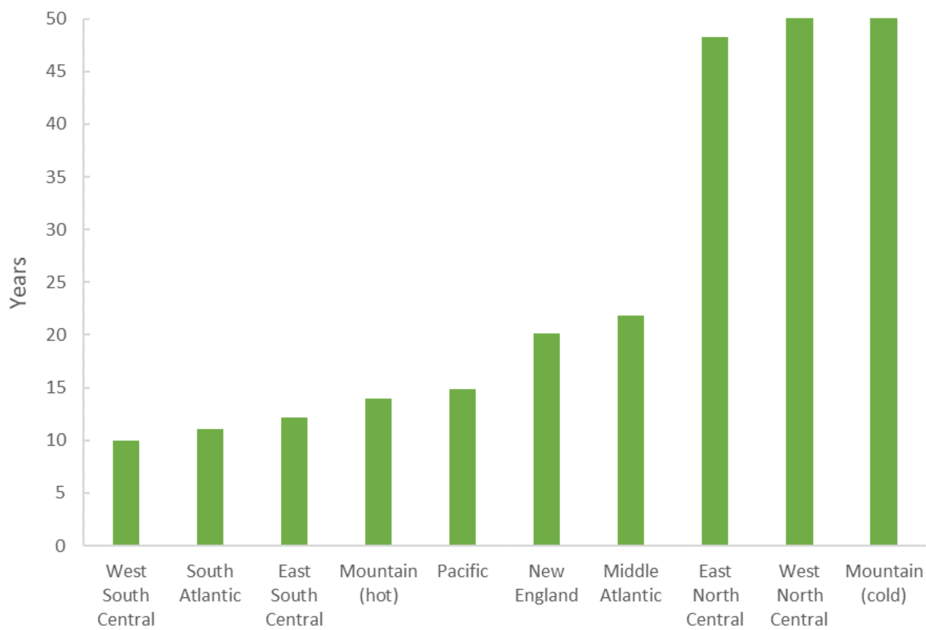

Figure 16. Median simple payback period by region from installing a rooftop heat pump when an existing packaged system with gas heat needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

[13] The simple payback periods we calculate and report are relative to a new gas-pack system meeting current efficiency standards.

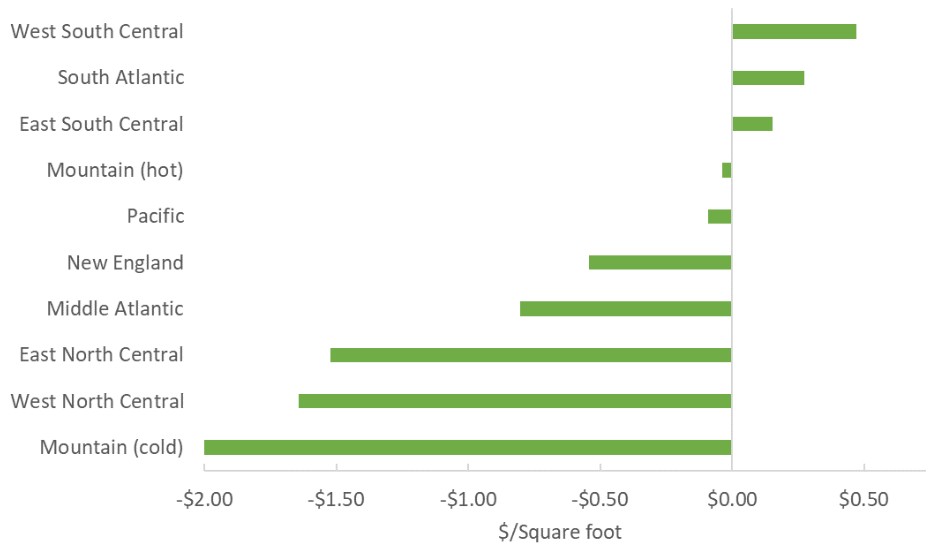

Figure 17. Median lifecycle savings by region for installing a rooftop heat pump when an existing packaged system with gas heat needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

Simple payback tends to be lowest for more energy-intensive building types (inpatient medical, laboratory, and food service) and for building types with relatively long operating hours (retail, offices, and nursing) (figure 18).[14] Median lifecycle cost savings per square foot of floor area are often positive for these same building types.

[14] We considered separating small offices from large offices but found that median simple payback periods for the two were very similar.

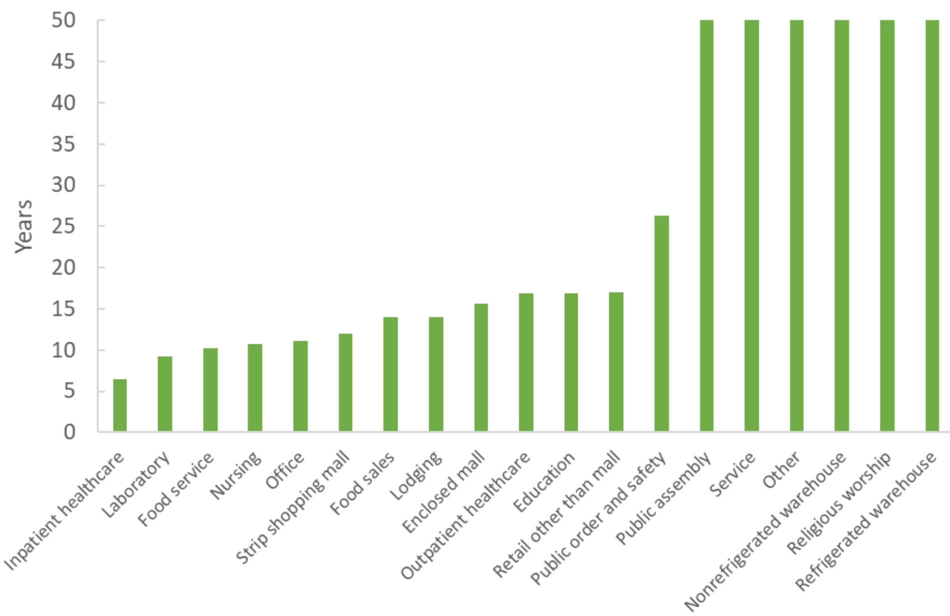

Figure 18. Median simple payback by building type for installing a rooftop heat pump when an existing packaged system with gas heat needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

Lifecycle cost savings tend to be highest for common building types, with simple payback periods below about 13 years (figure 19). However, these are only directional indications; the savings among buildings of the same type can vary substantially (figure 20).

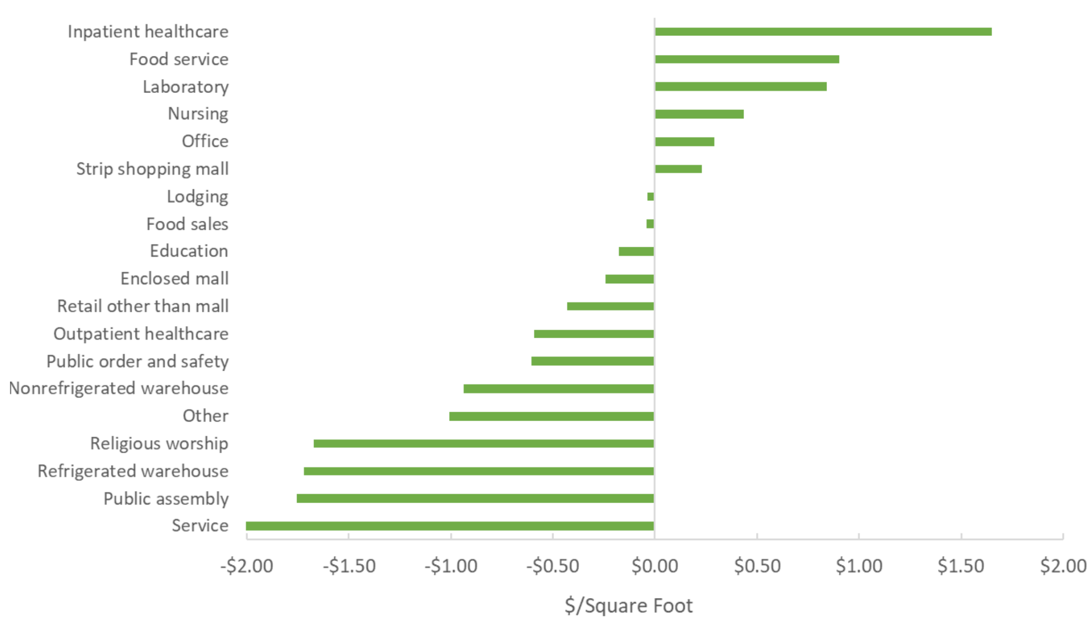

Figure 19. Median lifecycle cost savings per square foot by building type for installing a rooftop heat pump when an existing packaged system with gas heat needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

We prepared a distribution of simple payback periods across regions and building types (figure 20). These assume no financial incentives are provided. Simple payback periods are under 5 years for 7% of floor area, 5.1–10 years for 22% of floor area, and 10–21.67 years for 25% of floor area; 46% of floor area does not pay back.

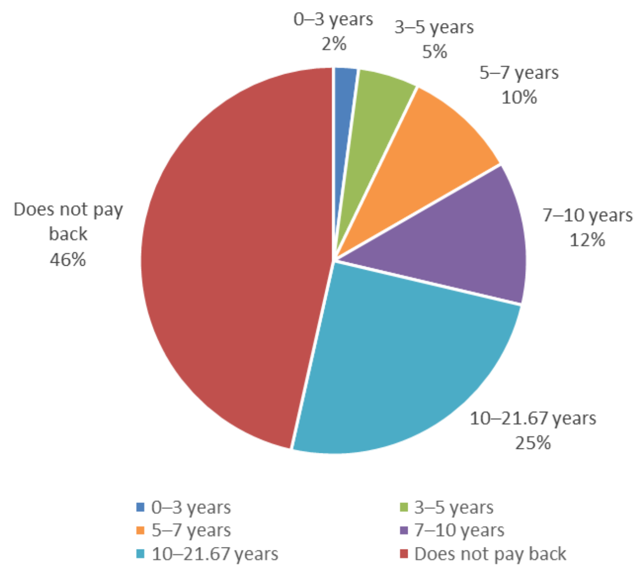

Figure 20. Distribution of simple payback periods under the medium-cost scenario for RTUs

We also examined simple payback as a function of building size and found that simple payback periods on average are shorter for buildings of 50,000 square feet or more than for smaller buildings (average payback of about 17 years for the larger buildings, 40 years for the smaller ones).

Finally, we looked at whether a less-efficient, less-expensive heat pump might improve electrification economics. Specifically, we looked at installing a 14.1 IEER heat pump instead of the 16.3 IEER heat pump we used in our primary analysis. We found that, on average, simple payback periods were slightly longer with the less-efficient heat pump.

VRF Systems: Another Potential Option

Our analysis of rooftop systems is based on a high-efficiency rooftop heat pump. Another option for some (but not all) buildings would be to use VRF systems coupled with a high-efficiency separate DOAS. The Northwest Energy Efficiency Alliance (NEEA) has installed such systems in seven commercial buildings ranging from a 1,360 square foot restaurant to a 25,200 square foot airport terminal building. Compared to equipment meeting local building code requirements, these systems reduced HVAC energy use by 45–85% with a simple average savings of 61%.[15] NEEA reports that the very-high-efficiency heat-recovery equipment is a critical component of achieving these savings (NEEA 2020). An analysis done for NEEA by Red Car Analytics (2019) of three prototypical buildings estimated installed system costs of $23.50–30.10 per square foot, which is $3.80–6.30 per square foot more than a replacement RTU, resulting in simple payback periods on the incremental investment of 6.2–8.4 years. This type of VRF plus DOAS is also being installed in a 71,000-square-foot office building in Tarrytown, New York; the first phase (serving part of the building) had good results, and the owner is now installing a system to serve the rest of the building (D. Cohan, Director of Policy and Technical Analysis, Institute for Market Transformation, pers. comm., June 22, 2020).

These results are promising, with higher energy savings and shorter simple payback periods than shown on average in our analysis of high-efficiency RTUs. However, sample sizes are small, and more demonstrations are needed to collect enough savings and cost information to do a much more comprehensive analysis.

Sensitivity Cases

Electrification economics are very sensitive to the cost of the system, so we also analyzed the economics using the low and high estimates of conversion costs. Payback periods were substantially shorter in the low-cost scenario and substantially longer in the high-cost scenario. In addition, we analyzed several other scenarios:

- An energy efficiency scenario in which we assumed that loads and capital costs are reduced 20% as a result of energy efficiency investments in a building at the time the system is replaced—for example, improved lighting (which reduces heat given off by lights), insulation, or better building controls. For purposes of this analysis, we assumed that the efficiency investments have a five-year simple payback using site-specific energy use and national average energy prices.
- A carbon-pricing scenario under which a $50/ton fee is levied on carbon dioxide emissions, on both natural gas used in gas heating systems and fossil fuels used to generate electricity.
- An incentive scenario under which a local program provides an incentive of $100/ton of cooling capacity to encourage electrification (this is approximately a midpoint incentive level according to our review of several current heat pump programs).

Results of these scenarios are illustrated by region in figure 21. In regions where the simple payback in the medium-cost scenario was 10–15 years, energy efficiency, carbon price, and incentives all reduced the simple payback to 6–10 years. However, in regions with much

[15] These savings are generally relative to an old constant-air-volume RTU system. Savings would be much lower relative to a much newer variable-air-volume RTU.

higher simple payback periods in the medium-cost scenario, carbon price appeared to have a larger effect than energy efficiency or incentives in bringing the payback down to within approximately 15 years.

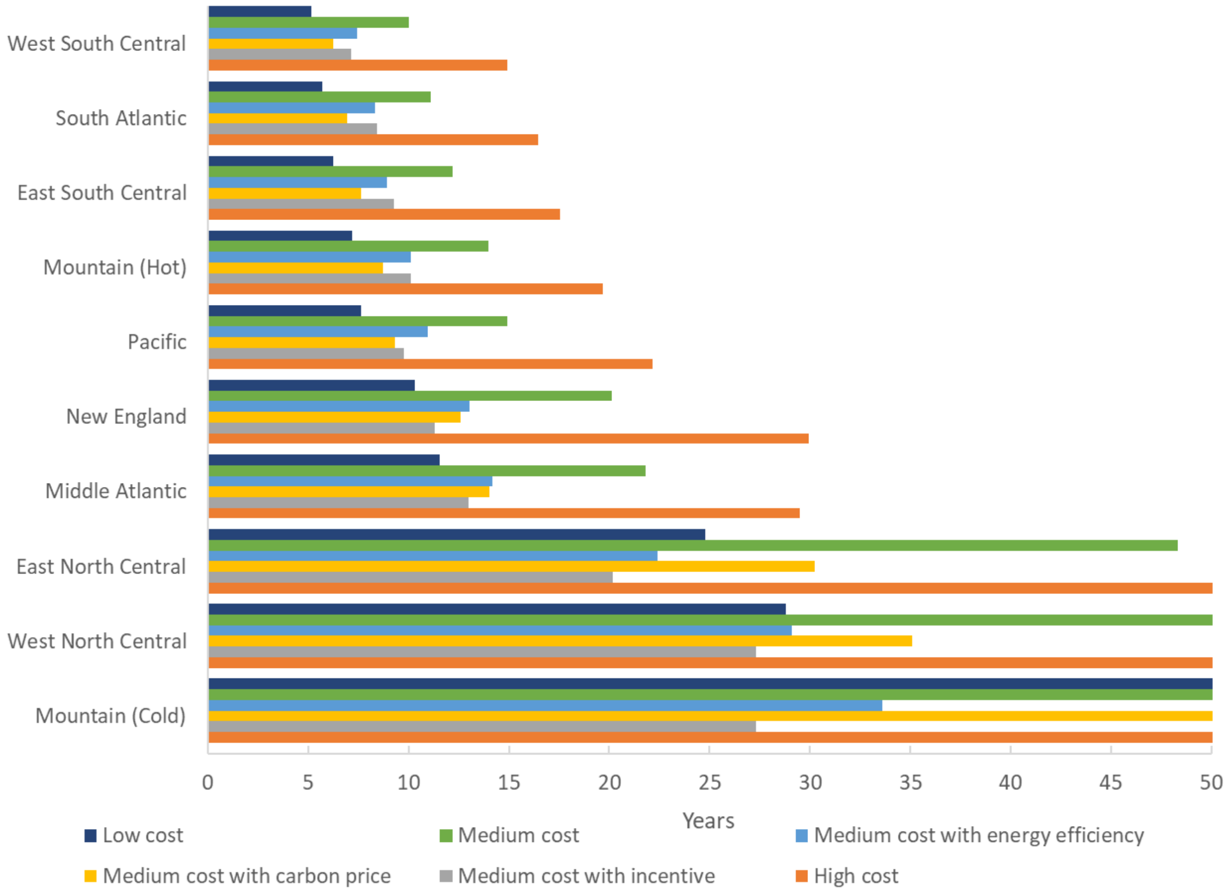

Figure 21. Median simple payback period by region for different scenarios for RTUs

We did some further analysis of simple payback periods at the national level. Figure 22 shows the number of conversions paying back over 0–10 years and 10.1–22.7 years (the average life of an RTU) and not paying back over the system life. In the medium-cost scenario, about 29% of floor area can be converted with a simple payback period of 10 years or less. This increases to 39–44% in the efficiency, carbon price, and incentive scenarios individually and to 72% in a scenario with all three combined.

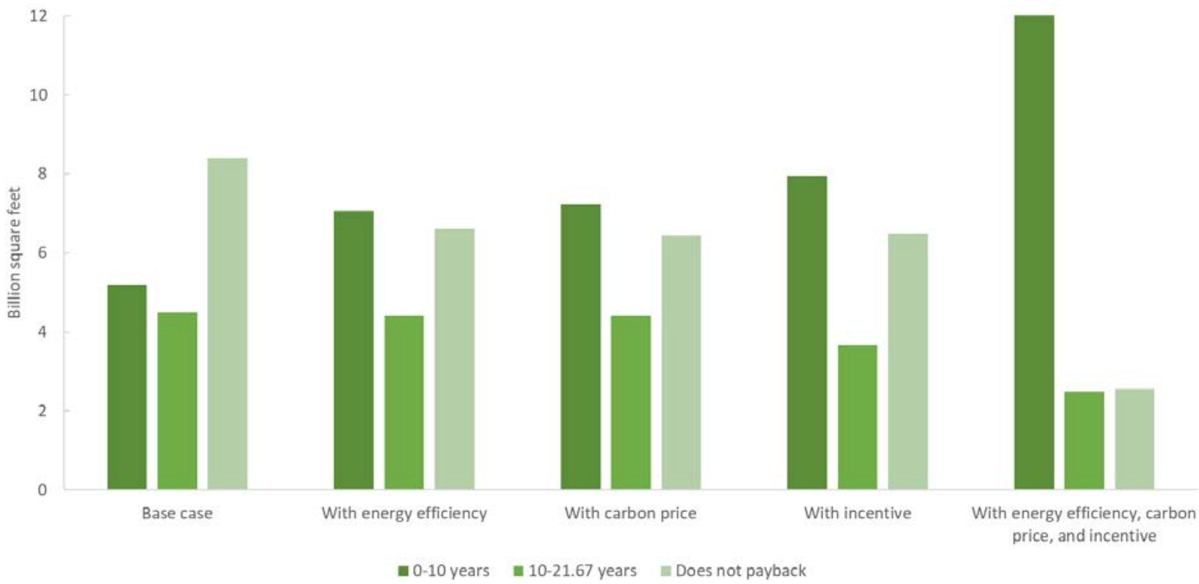

Figure 22. Distribution of simple payback periods under different scenarios for RTUs

Emissions

Electrification is done in part to reduce emissions, particularly GHG emissions. We found that electrifying all RTUs with payback periods of 15-years or less will reduce GHG emissions in most regions. Emissions reductions are highest in the West North Central (e.g., Minnesota, Iowa, and Missouri); Pacific (California, Oregon, Washington, and Alaska); and New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont) regions. The East North Central and Middle Atlantic regions are close behind. All are populous regions with large heating loads (figure 23)[16]. These emissions reductions are based on average regional emissions in 2030 as estimated by EIA (2020a).

In addition to GHG emissions reductions, regions with clean power generation (either now or in the future) will also often show reductions in other emissions such as nitrogen oxides.

[16] California is the one exception to the large heating-load trend.

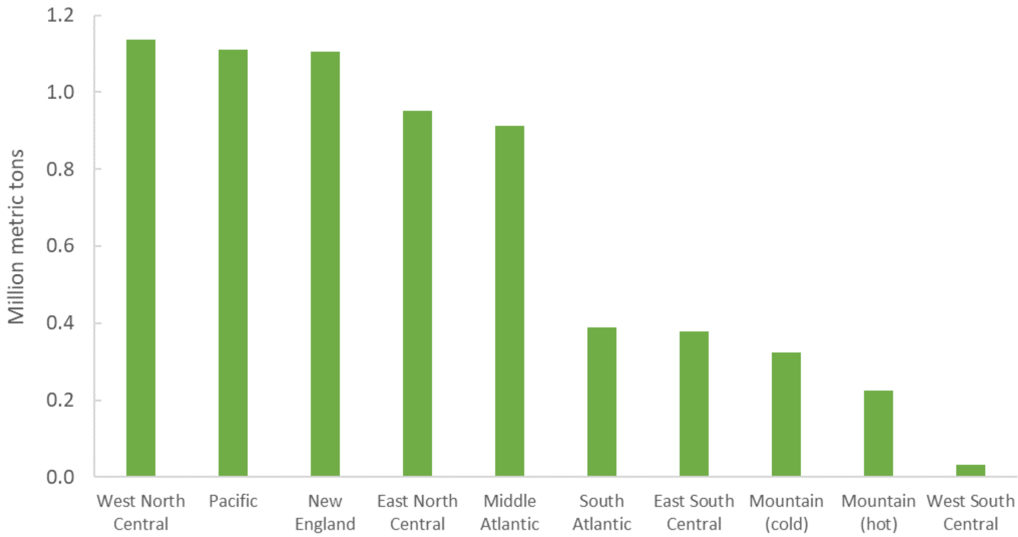

Figure 23. GHG emissions reductions by region for RTU replacement. Only applications with simple payback periods shorter than 15 years are included in this figure.

Case Study

An example of a rooftop heat pump conversion is at Vishay Tansitor, a mixed-use light industrial facility that produces and ships electronic parts (e.g., capacitors) in Bennington, Vermont. It had a 30-year-old 10-ton RTU with electric heat serving shipping/receiving that was at the end of its life. Vishay Tansitor looked at a replacement electric resistance heat system, a propane system, and a high-efficiency heat pump and ultimately chose the heat pump. The conversion cost about $12,500 more than a replacement all-electric system and about $11,500 more than a propane system but saves about $2,750 annually compared to an electric resistance system and about $2,650 compared to a propane system (VEIC 2015). Thus, relative to propane, the heat pump pays back in about four years.

GAS FURNACES REPLACED WITH HEAT PUMPS

Our analysis of furnaces was based on buildings in CBECS that now use gas furnaces for space heating. CBECS does not provide propane consumption data, and very few buildings in the CBECS sample have oil furnaces; therefore, we did not analyze these fuels. A total of 319 buildings are included in our furnace analysis, which represents about 5% of the total buildings in CBECS. Some of these furnaces are units that might also be used in residences, and many others are essentially larger versions of residential-style furnaces. This analysis compared a commercial furnace meeting the minimum efficiency standards set in the federal Energy Policy Act of 1992, which requires an 80% thermal efficiency for gas furnaces with a high-efficiency heat pump. The type of heat pump depends on the climate and type of air-conditioning system it replaced, all based on composite units offered by four major manufactures: cold-climate split-system heat pumps (20.0 SEER, 11.8 HSPF)[17], warm-climate split-system heat pumps (20.9 SEER, 10.9 HSPF), and (all climates) packaged heat pumps (15.3 SEER, 8.1 HSPF). In general, our results are broadly similar to the results for RTUs discussed in the previous section.

Energy Savings

In all regions, the high-efficiency heat pumps reduce site energy use. Savings are highest in cold, populous regions because that is where energy use is highest. For example, the East North Central region (Ohio and vicinity) has the highest available savings. In addition to heating savings, we find ventilation energy use reductions (the high-efficiency heat pumps all have variable-speed or multiple-speed ventilation fans) and cooling savings (high-efficiency heat pumps have higher cooling season efficiencies than standard RTUs). For these latter reasons, savings are also high in the Middle Atlantic, West South Central (Texas and vicinity), and South Atlantic regions. Annual savings by region are illustrated in figure 24. These calculations assume that all existing furnaces are replaced by heat pumps when the existing systems need replacement; thus, these savings will be fully achieved in just over 20 years.

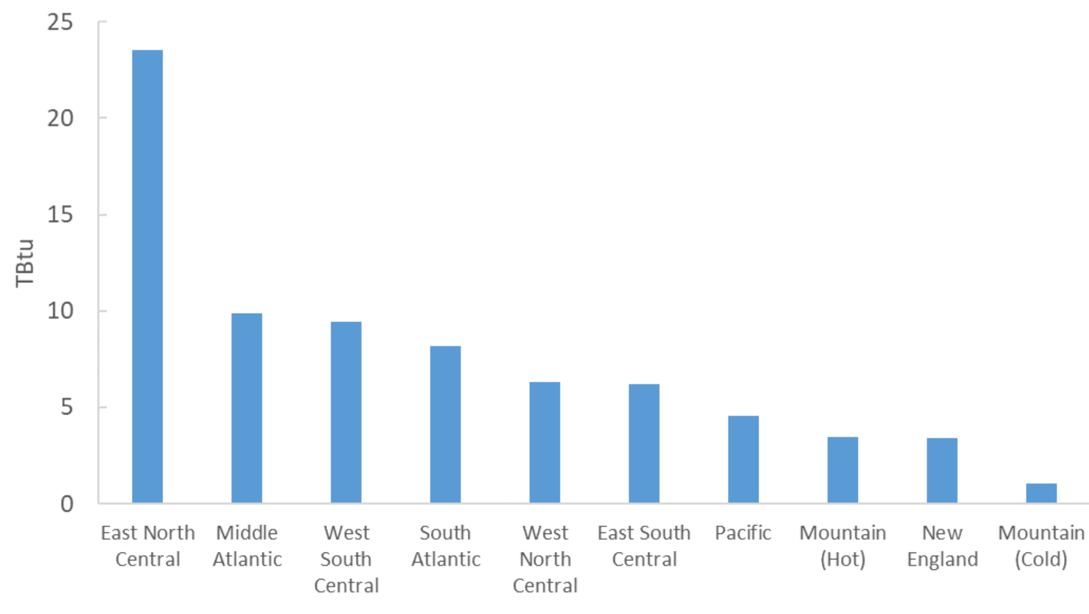

Figure 24. Total energy savings by region from installing a heat pump when an existing commercial gas furnace needs to be replaced

Total energy savings per building are highest for offices and religious facilities, building types that are numerous and frequently use furnaces (figure 25).

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[17] SEER stands for Seasonal Energy Efficiency Ratio, which is a weighted average of cooling energy efficiency ratings of the unit as tested at different temperatures. HSPF stands for Heating Seasonal Performance Factor, which is a heating efficiency rating for heat pumps based on the ratio of heat provided to energy consumed.

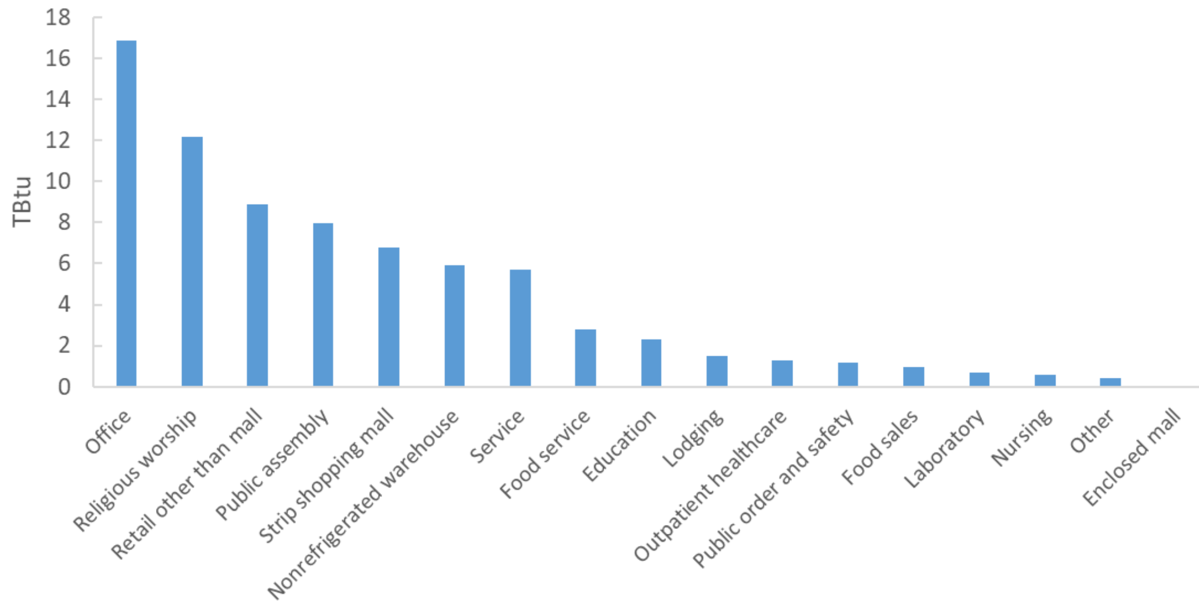

Figure 25. Total energy savings by building type from installing a heat pump when an existing commercial gas furnace needs to be replaced

Economics

While the energy savings are highest in a cold region—East North Central—the economics of converting to a high-efficiency heat pump are much better in warm regions. Our economic analysis used incremental costs from Southern California Edison's Heat Pump, Unitary and Air-Cooled HVAC, Commercial – Fuel Substitution workpaper[18] and an equipment life of 15.63 years from the DOE Residential Central Air Conditioners and Heat Pumps Technical Support Document (SCE 2020, DOE 2016). We assumed that in the base case the existing air conditioner would need replacement in five years. On the basis of these assumptions, as well as changes in natural gas and electricity use from our energy savings analysis, we found that the economics of high-efficiency packaged heat pumps vary widely by region. In warmer regions, the median simple payback in our midpoint price scenario is about 8–10 years. In colder regions, the median simple payback is 12–18 years (figure 26). This is sometimes longer than the approximately 16-year median life of the equipment; therefore, in some cases, the electrification option is not cost effective without incentives or other inducements. This is also shown in our analysis of median lifecycle costs (figure 27).

[18] Material costs for equipment less than 65 kBtu/h were obtained from several online sources, including www.acwholesalers.com, www.acdirect.com, and www.nationalairwarehouse.com. Labor costs were obtained from RSMeans Online. ACEEE found these incremental costs to be comparable to the DOE Residential Central Air Conditioning and Heat Pump and Commercial Warm Air Furnaces Technical Support Documents (DOE 2016, DOE 2015a).

With a 16-year equipment life, when simple payback periods exceed about 10 years, lifecycle costs are often negative at the discount rate we used (5% real[19]).

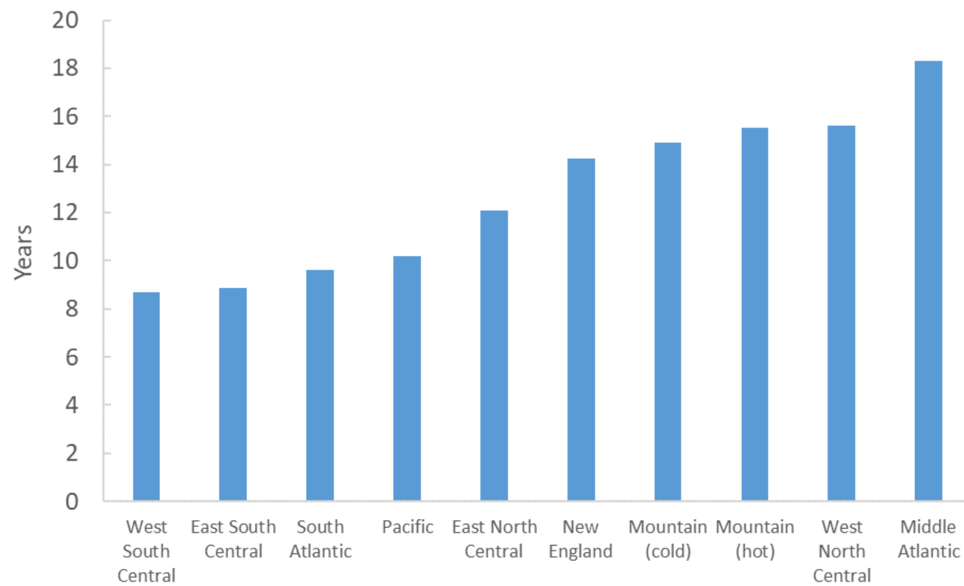

Figure 26. Median simple payback period by region from installing a heat pump when an existing gas furnace needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

[19] In examining equipment efficiency standards, DOE typically uses both a 3% societal discount rate and a 7% consumer discount rate. We use the midpoint between these two levels (e.g., see DOE 2016b).

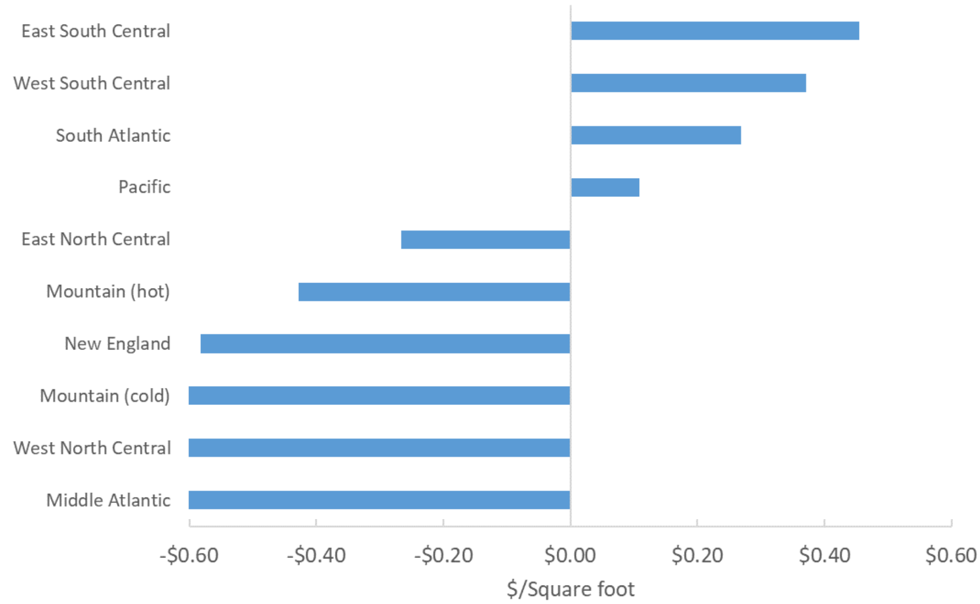

Figure 27. Median lifecycle cost savings by region for installing a heat pump when an existing gas furnace needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

Simple payback tends to be lowest for more energy-intensive building types (food sales) and for building types with relatively long operating hours (offices and lodging) (figure 28). Median life-cycle costs per square foot of floor area are often positive for these same building types (figure 29).

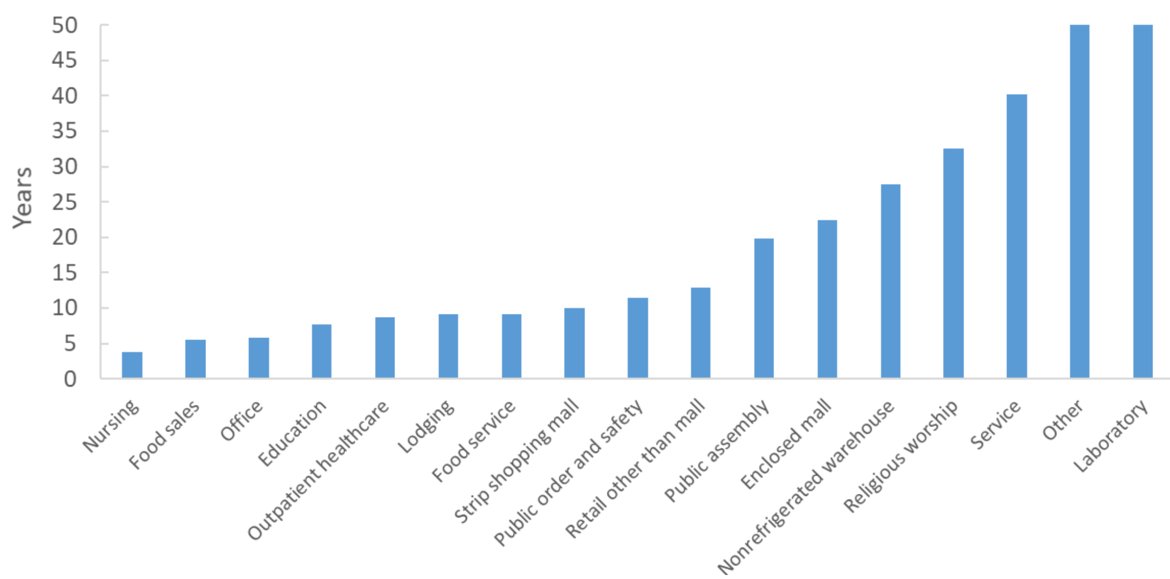

Figure 28. Median simple payback by building type for installing a rooftop heat pump when an existing packaged system with gas heat needs to be replaced

Lifecycle cost savings tend to be highest for common building types with better than median simple payback periods (figure 29). However, these are only directional indications—among buildings of the same type, savings show substantial variability (figure 30).

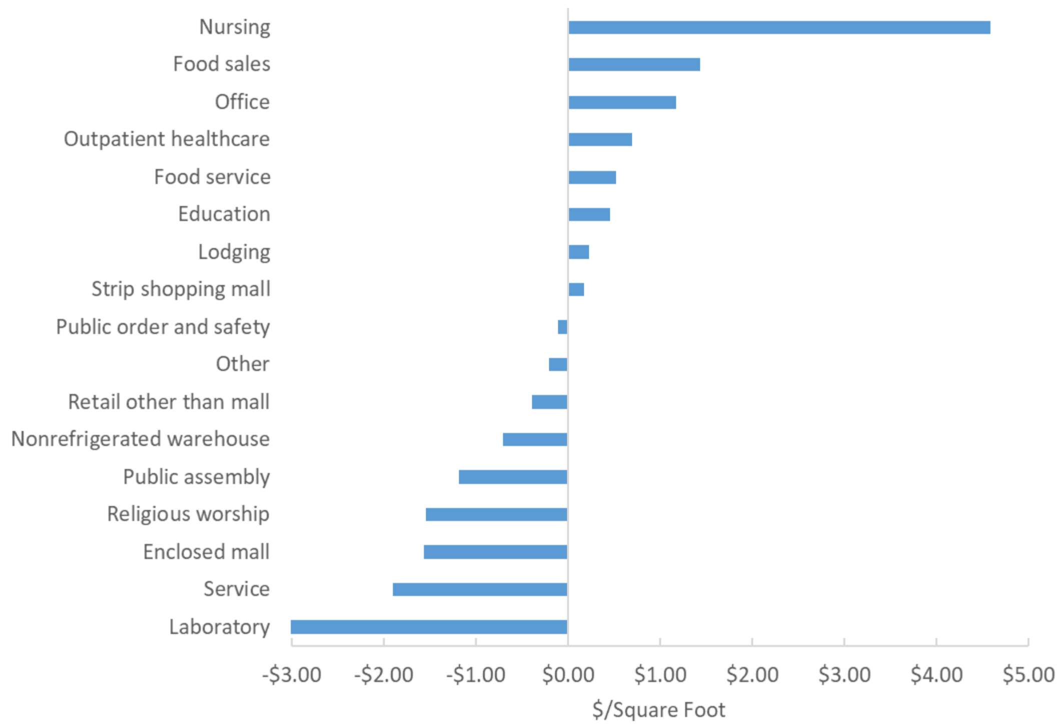

Figure 29. Median lifecycle cost savings per square foot by building type for installing a rooftop heat pump when an existing packaged system with gas heat needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

We prepared a distribution of simple payback periods across regions and building types (figure 30). Simple payback periods are shorter than 5 years for 13% of floor area, 5.1–10 years for 22% of floor area, and 10–15.63 years for 23% of floor area (15.63 years is the average life of this equipment); 42% of floor area does not pay back. Relative to the RTU analysis in the previous section, payback periods are a little shorter.

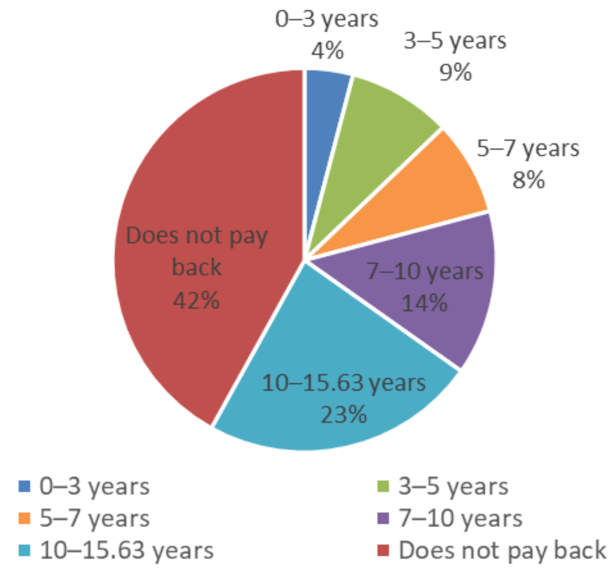

Figure 30. Distribution of simple payback periods under the medium-cost scenario for furnaces units

We also examined simple payback as a function of building size and found that simple payback periods on average are shorter for buildings of 25,000 square feet or less than for larger buildings (about 11 years average payback for the smaller buildings, 20 years for the larger ones).

Sensitivity Cases

Electrification economics are very sensitive to the cost of the system, so we also analyzed the economics using the low and high estimates of conversion costs, as we did for RTUs. For split systems, we assumed the difference between the low and high costs were similar to RTUs and used the average cost ±41%; we used the same kW/ton costs for packaged heat pumps as we did for heat pump RTUs. The high-cost scenario increased paybacks by about 50%; the low-cost scenario reduced them by about one-third.

Likewise, we also included energy efficiency, carbon-pricing, and incentive scenarios with the same assumptions as we described for RTUs above. Results of these scenarios are illustrated by region in figure 31. In regions where the simple payback in the medium-cost scenario was seven to nine years, energy efficiency and incentives reduced the simple payback about two years, and carbon pricing reduced the simple payback about one year. However, in regions with much longer simple payback periods in the medium-cost scenario, even with efficiency, carbon pricing, or incentives, the simple payback was still generally over 10 years.

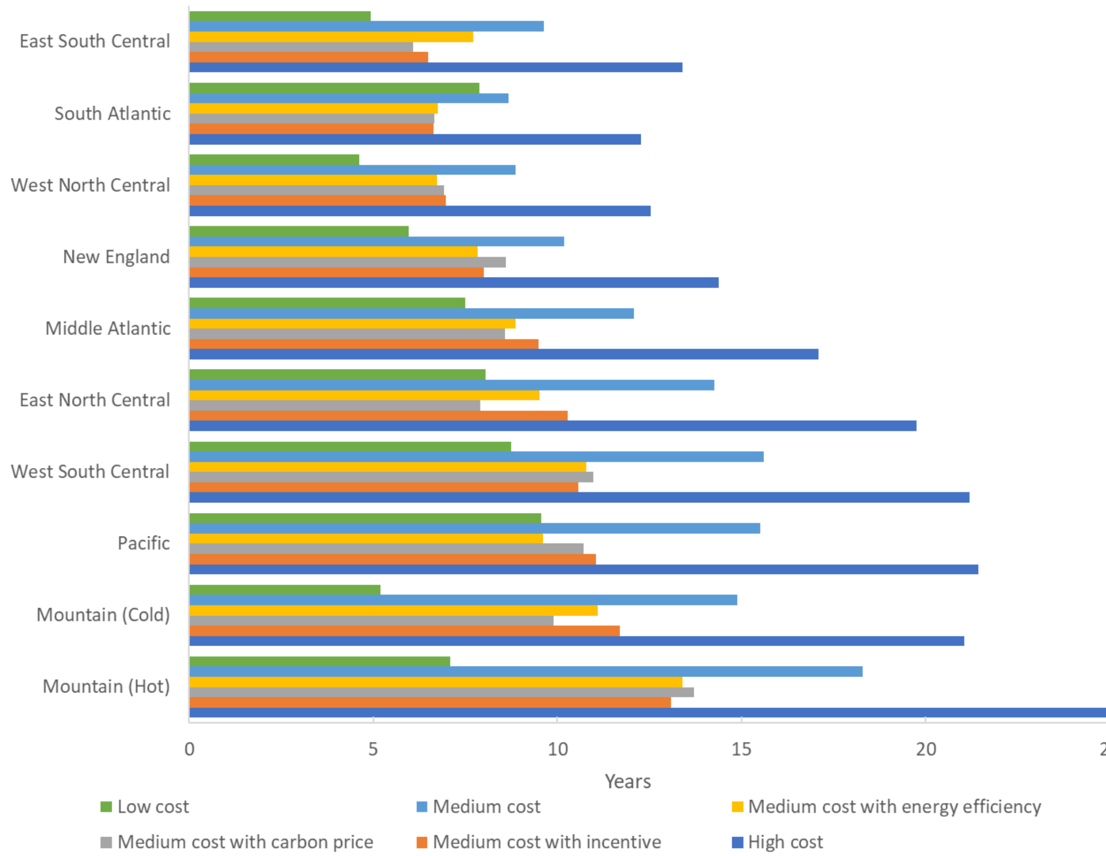

Figure 31. Median simple payback period by region for different scenarios for replacing furnaces with heat pumps

We also did some further analysis of simple payback periods at the national level. Figure 32 shows the number of conversions paying back over 0–10 years and 10.1–15.63 years (the average life of residential-sized air conditioners and heat pumps) and not paying back over the system life. In the medium-cost scenario, about 35% of floor area can be converted with a simple payback period of 10 years or less. This increases to 46–51% in the efficiency, carbon price, and incentive scenarios individually and to 79% in a scenario with all three combined.

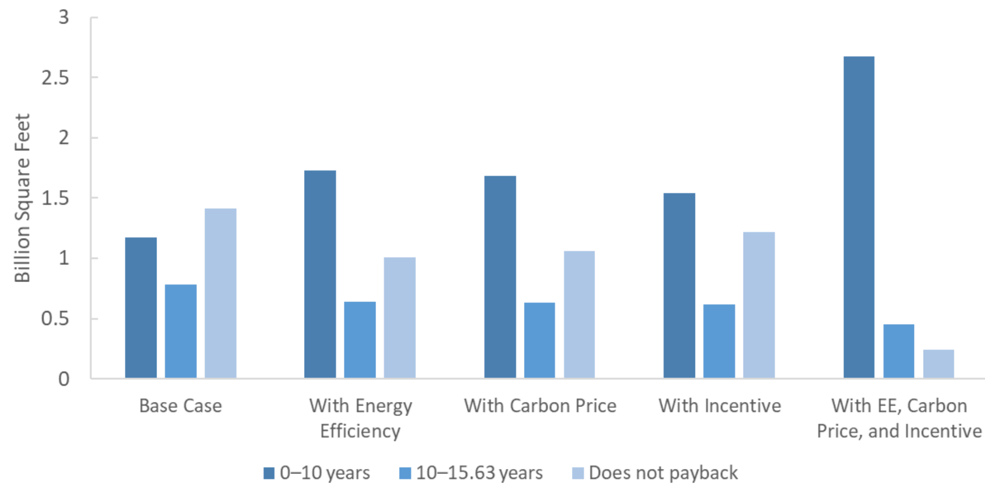

Figure 32. Distribution of simple payback periods under different scenarios for replacing furnaces with heat pumps

Emissions

A primary purpose of electrification is to reduce emissions, particularly GHG emissions. As with RTUs, we found that if we convert all furnaces to heat pumps in applications with a 15-year payback or less, emissions reductions are highest in the East North Central region, with the West South Central region coming in second. Both are populous regions, the former with large heating loads (figure 33).

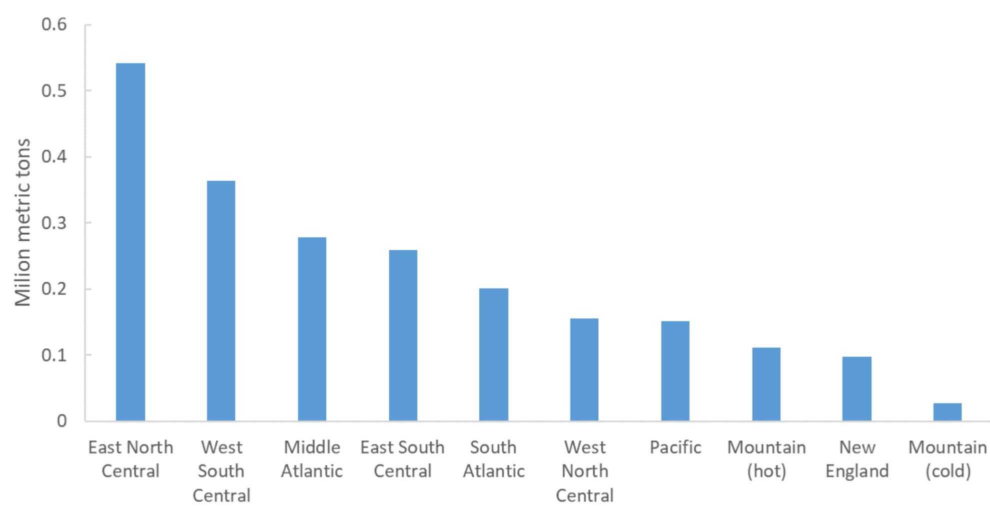

Figure 33. Emissions reductions by region for replacing gas furnaces. Only applications with simple payback periods shorter than 15 years are included in this figure.

BOILERS AND SPACE HEATERS REPLACED WITH VRF HEAT PUMPS

Introduction

Our analysis of boilers and space heaters included smaller gas and oil boilers (those used in buildings smaller than 100,000 square feet, as well as gas and oil space heaters). Larger buildings typically also have chillers and are discussed in the next section of this report.

Buildings with boilers and space heaters often have no duct systems in place; therefore, our analysis looks at the costs, savings, and economics of installing ductless or VRF heat pumps to provide heating and air-conditioning when the existing system needs to be replaced. This analysis covers about 8% of total commercial building floor area. We used ductless heat pumps for buildings below 5,000 square feet and VRF systems above this threshold, as explained in the Appendix. A total of 544 buildings are included in the boiler and space-heater analysis, which is about 8% of the total buildings in CBECS. Our analysis compares either a commercial boiler or space heater meeting the minimum efficiency standards established by DOE (80% thermal efficiency for boilers and space heaters) with a high-efficiency heat pump. Most of these buildings also use room or central air conditioners for cooling, and for the boiler/space heater base case we assumed that these systems will be replaced with a similar system meeting current minimum efficiency standards. We also considered buildings with no cooling system. For ductless heat pumps, we used a system with a rated SEER of 30 and COP (at 47° F) of 4.3; for VRF, we used a system with 32 IEER and 12.6 HSPF.[20] This system provides both heat and air-conditioning.

Overall, ductless and VRF systems have higher efficiencies than rooftop and other ducted heat pumps, but they are more expensive.[21] Specific results for energy and emissions savings and economics are discussed in the following sections.

While our analysis is based on VRF and other ductless systems, there are other options for replacing boilers, such as air-to-water heat pumps and, for appropriate applications, ground-source heat pumps.[22] Within the scope of this project, we could examine only one system; we chose VRFs.

Energy Savings

Ductless and VRF heat pumps reduce energy use in all regions. Energy savings are highest in the Middle Atlantic and East North Central regions, both of which have large populations, extensive use of boilers (more popular in the Northeast and Midwest), and cold climates. Savings are smaller in less-populous regions, regions with limited use of boilers, and warm regions (figure 34).

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[20] We modified both cooling and heating ratings, as described in the Appendix.

[21] Efficiency ratings are nominally substantially higher for VRF systems, but these ratings need to be discounted, as explained in the Appendix. With this adjustment, VRF efficiencies are still somewhat higher.

[22] For example, in London, England, a project is now under way to replace existing gas boilers with water-source heat pumps in three high-rise multifamily buildings (Carbon Trust 2020).

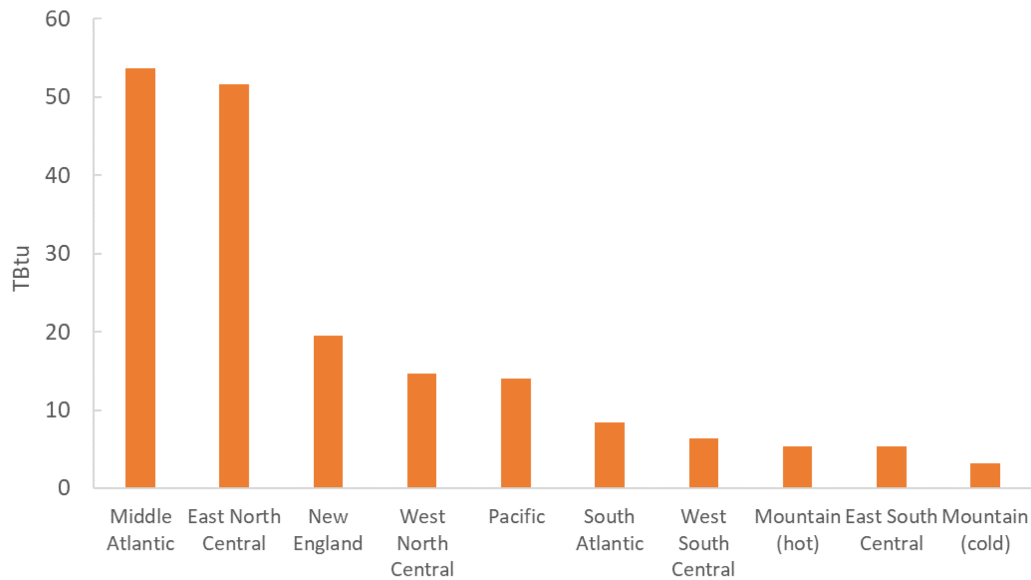

Figure 34. Total energy savings by region from installing a ductless or VRF heat pump when an existing boiler or space heater needs to be replaced

Total energy savings are highest for offices and educational facilities—building types that are numerous and frequently use boilers (figure 35).

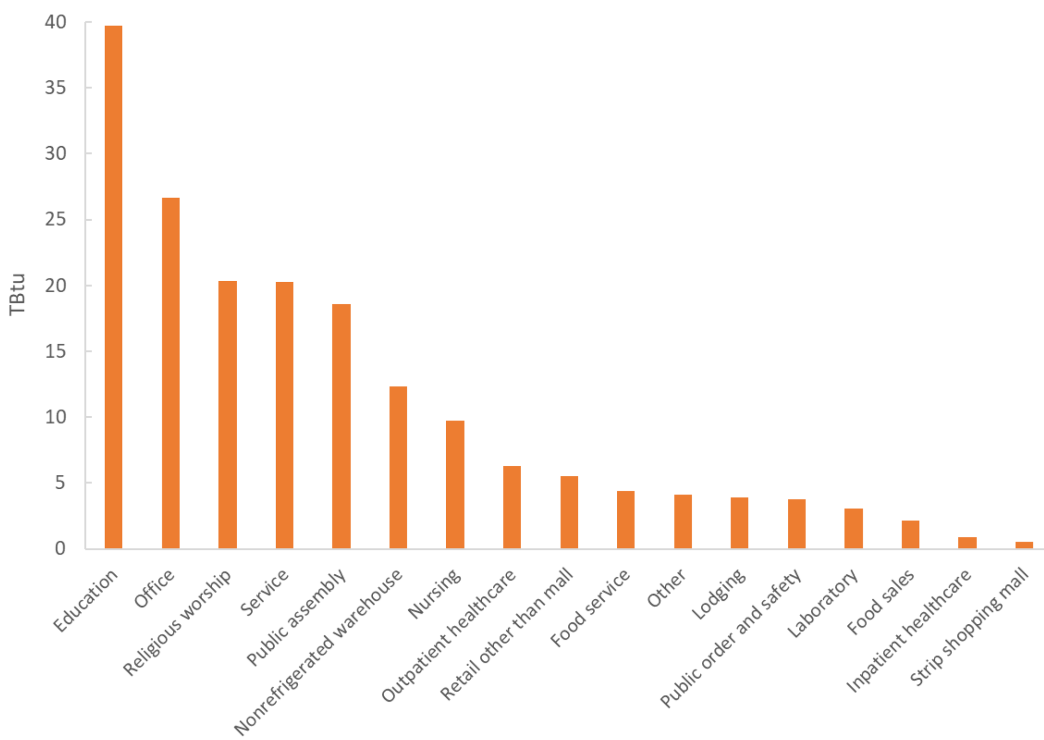

Figure 35. Total energy savings by building type from installing a ductless or VRF heat pump when an existing boiler or space heater needs to be replaced.

Economics

While the energy savings are highest in cold regions, the economics of converting to a ductless or VRF heat pump are better in warm regions. Our economic analysis used incremental costs from RS Means and a study by Red Car Analytics (2019) on VRF systems. We used a 16-year life for the ductless and VRF heat pumps and adjusted costs for systems with longer or shorter lives to 16 years; details are in the Appendix.

On the basis of these assumptions, as well as changes in fuel and electricity use from our energy savings analysis, we found that the economics of ductless and VRF buildings are generally challenging in the buildings we examined. In most regions, median simple payback periods are longer than 50 years, and even in the East South Central region (e.g., Tennessee), median simple payback periods are still about 30 years (figure 36). This is substantially longer than the average equipment life of 16 years; therefore, for these applications, the electrification option is often not cost effective without incentives or other inducements. This is also shown in our analysis on median lifecycle costs (figure 37). With an equipment life of 16 years, when simple payback periods exceed about 10 years, lifecycle costs are often negative at the discount rate we used (5% real).

This analysis does not include use of a high-performance DOAS, which increases both energy savings and costs. Instead, we assume that the current ventilation system continues to function.[23] As discussed in the RTU section, such systems have achieved paybacks of six to eight years in a few applications, but data on more projects are needed.

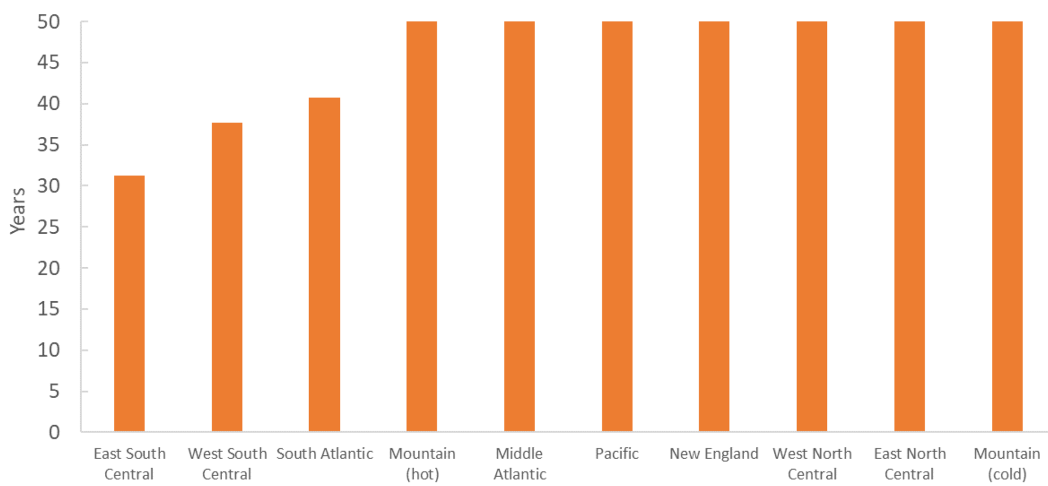

Figure 36. Median simple payback period by region from installing a ductless or VRF heat pump when an existing boiler or space heater needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

[23] As noted by NEEA (2020), energy savings can be increased substantially with a high-efficiency DOAS, but costs will also increase. These systems are promising, but there is not yet enough experience for us to base our analysis on such a case.

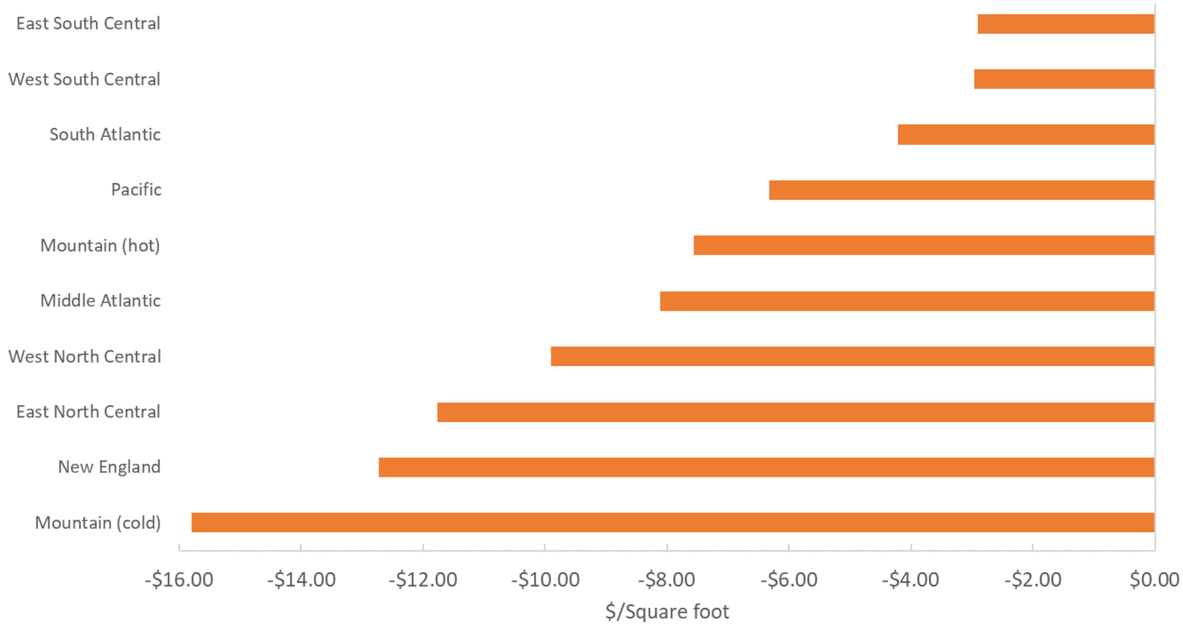

Figure 37. Median lifecycle cost savings by region for installing a ductless or VRF heat pump when an existing boiler or space heater needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

Simple payback tends to be shortest for more energy-intensive building types and those with relatively long operating hours, such as inpatient healthcare (figure 38).

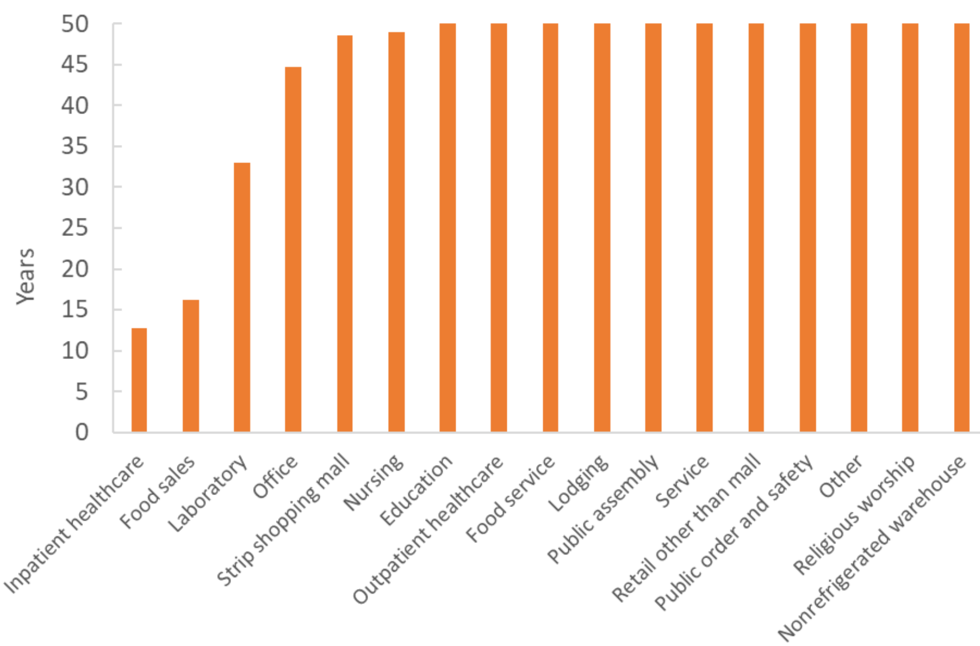

Figure 38. Median simple payback by building type for installing a ductless or VRF heat pump when an existing boiler or space heater needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

Lifecycle cost savings tend to be similarly high for energy-intensive buildings or those with long operating hours, such as inpatient healthcare (figure 39).

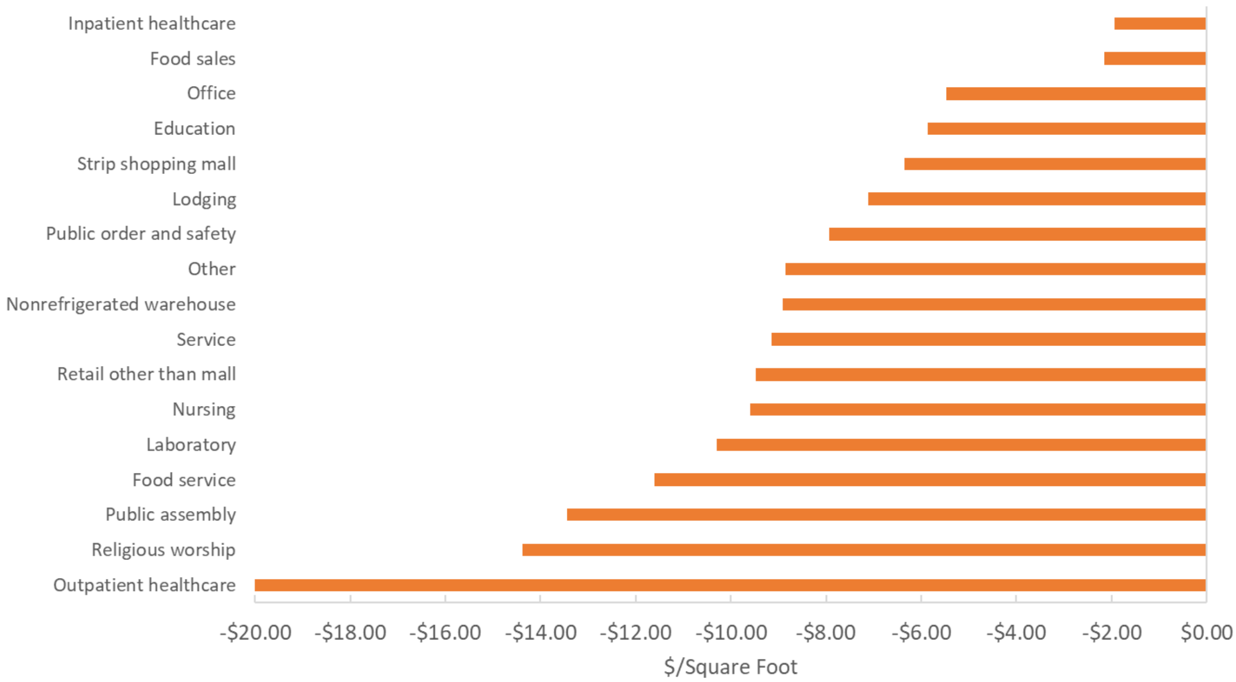

Figure 39. Median lifecycle cost savings per square foot by building type for installing a ductless or VRF heat pump when an existing boiler or space heater needs to be replaced. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

We prepared a distribution of simple payback periods across regions and building types (figure 40). Simple payback periods are shorter than 10 years for 3% of floor area and 10–16 years for 4% of floor area (16 years is the average life of this equipment); 94% of floor area does not pay back. Compared to the RTU and furnace analyses in previous sections, payback periods for ductless or VRF heat pumps are generally much longer.

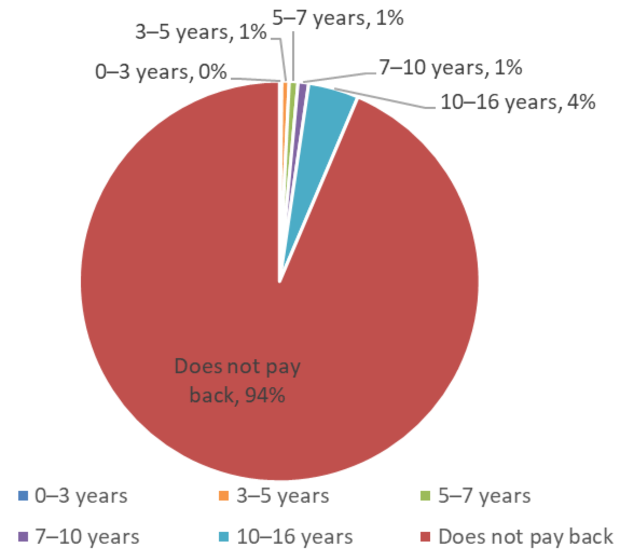

Figure 40. Distribution of simple payback periods under the medium-cost scenario for replacing boilers and space heaters with ductless and VRF heat pumps

We also examined simple payback as a function of building size and found that simple payback periods on average are shorter for larger (above about 50,000 square feet) buildings than for smaller buildings (a median payback of 62 years for buildings above this threshold but over 500 years for smaller buildings). However, even the larger buildings, on average, were not cost effective.

To further examine where VRF systems might be cost effective, we segmented our analysis into buildings that presently do and do not have air-conditioning and separated buildings with boilers from those with space heaters. We found that when we look just at buildings with boilers that presently have packaged or split-system air-conditioning (and hence can save energy and money with a more efficient air-conditioning system), the simple payback is improved by 34% on average. We return to this scenario in our sensitivity cases.

Sensitivity Cases

Electrification economics are very sensitive to the cost of the system, so we also analyzed the economics using the low and high estimates of conversion costs, as we did for RTUs and furnaces. As with the other system types, we assumed the difference between the low and high costs were ±41% (specifics discussed under RTUs). The high-cost scenario increased paybacks substantially while the low-cost scenario reduced them a little (costs relative to energy savings are still high).

Likewise, we also included energy efficiency, carbon-pricing, and incentive scenarios with the same assumptions as used for RTUs except that we used incentives of $500 per ton on the basis of a recent review of ductless heat pump incentives (Nadel 2020). Results of these scenarios are illustrated by region in figure 41. Overall, these three scenarios had roughly similar impacts. For example, in the East South Central region, simple paybacks decreased from a median of about 31 years to 17–20 years in the scenarios.

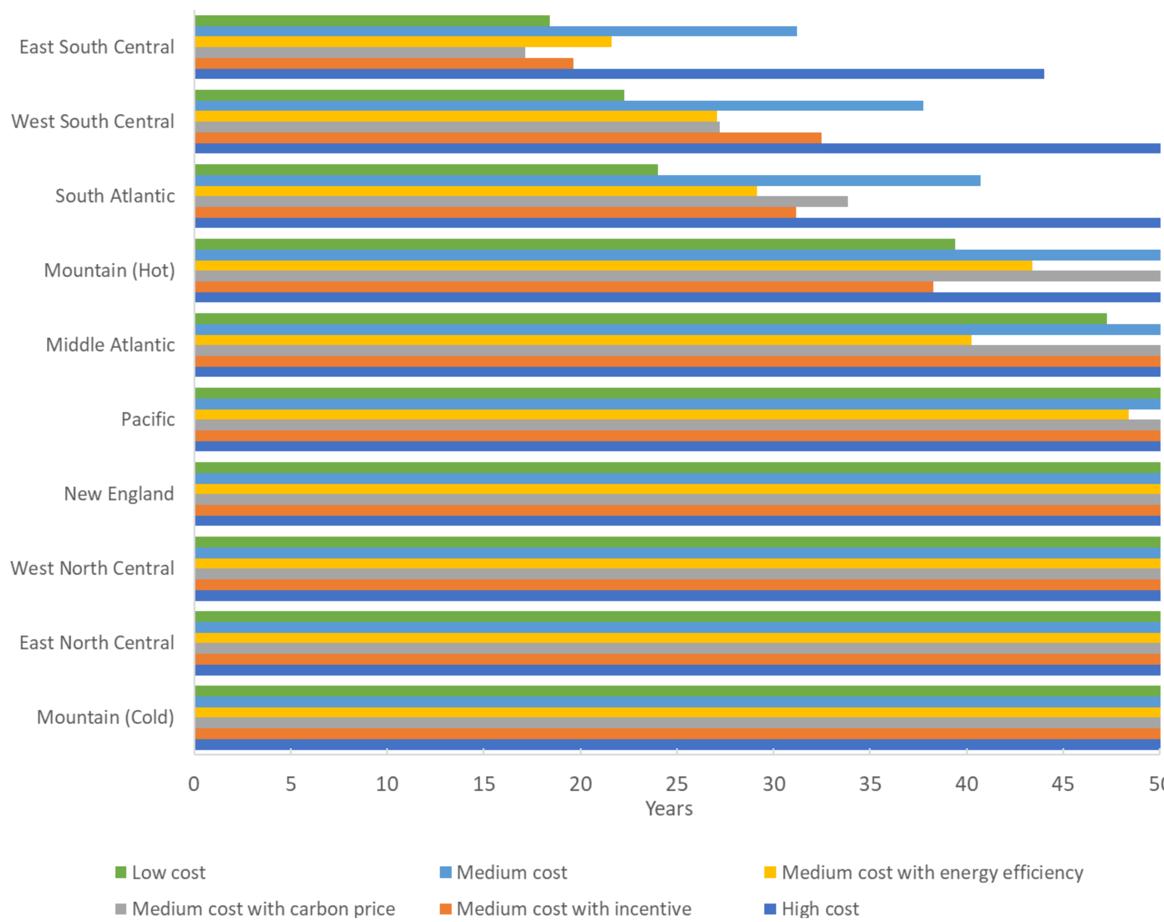

Figure 41. Median simple payback period by region for different scenarios for replacing boilers and space heaters with ductless and VRF heat pumps

These scenarios can also be combined. Figure 42 shows the amount of floor area that falls into different payback bins as energy efficiency, incentives, and carbon pricing are combined. Overall, with all three, about 17% of floor area has a simple payback of less than 10 years, and even with all three, about 72% never pays back over the life of the equipment.

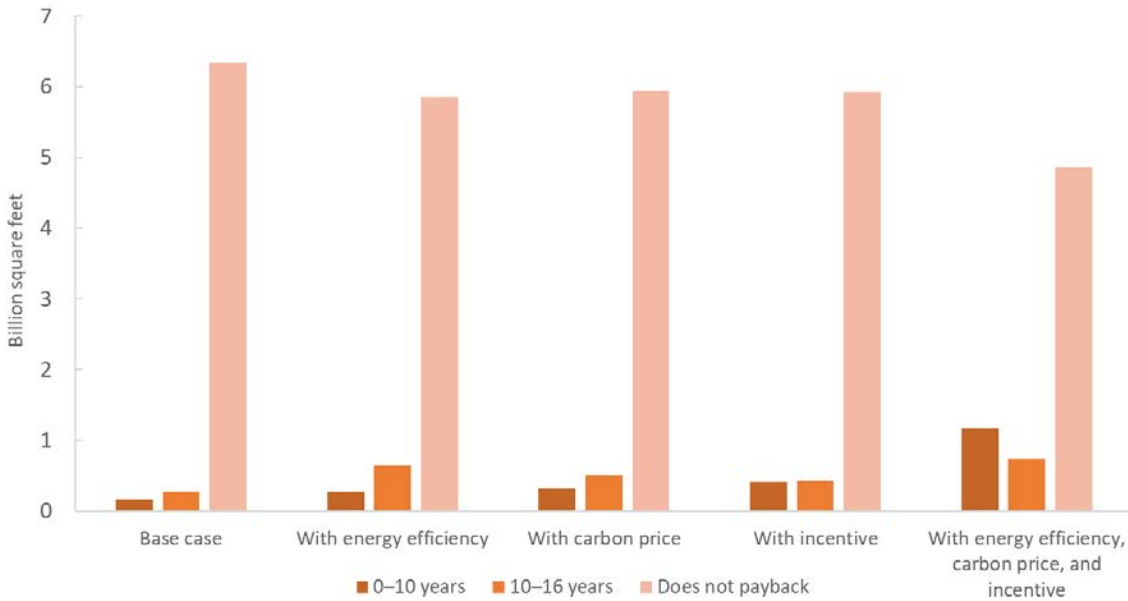

Figure 42. Median simple payback period for different scenarios for replacing boilers and space heaters with ductless and VRF heat pumps

Finally, we conducted the same set of sensitivity analyses on the subset of buildings with split-system or packaged air-conditioning and boilers. For these buildings, as shown in figure 43, simple payback periods can be as short as 8–14 years in the East South Central, South Atlantic, and Pacific regions. We can conclude that VRF will be more cost effective when replacing high-cost equipment such as boilers and central air-conditioning systems but will struggle to compete with low-cost systems such as space heaters and room air conditioners.

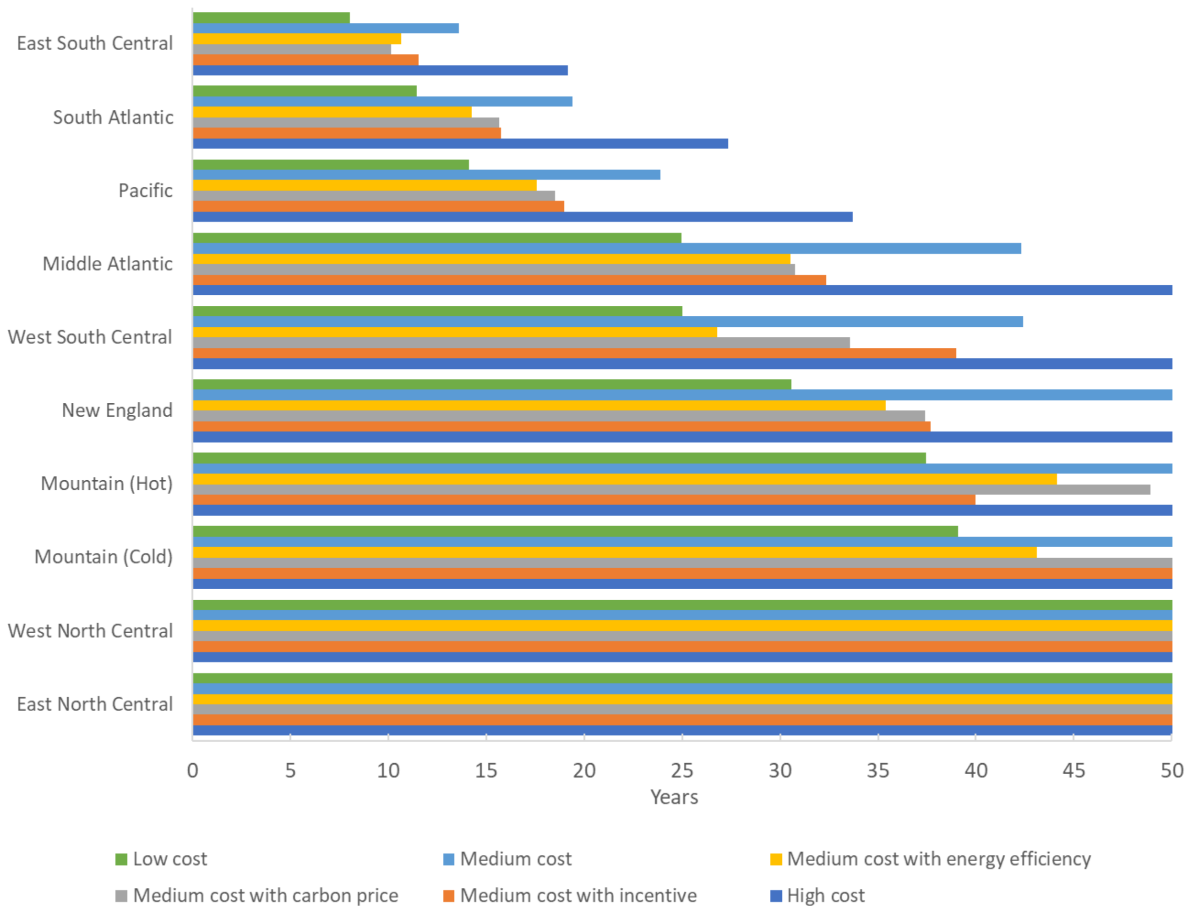

Figure 43. Median simple payback period for different scenarios for replacing boilers with ductless and VRF heat pumps in buildings that presently have split-system or packaged air-conditioning

Emissions

Electrification is done in part to reduce emissions, particularly GHG emissions. Unlike for the other analyses, we find (figure 44) that most of the emissions reductions are in the Middle Atlantic region because the population is large, boilers are relatively common, and the economics are more favorable than in colder regions. Also note that the amount of emissions reductions (about 50 million metric tons in total) is substantially lower than for the RTU analysis and about the same as for the furnace analysis.

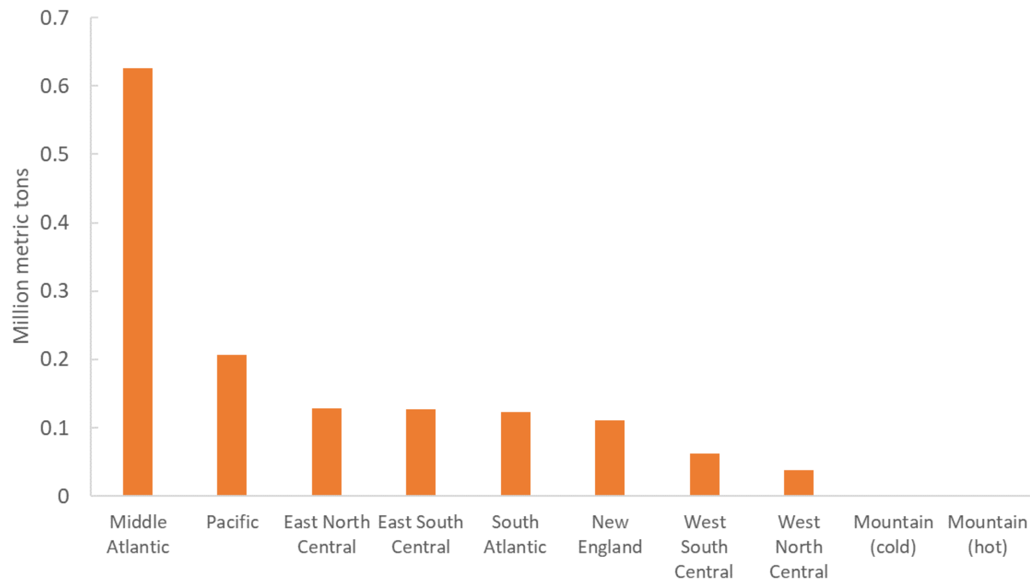

Figure 44. Emissions reductions by region for replacing boilers and space heaters with ductless and VRF heat pumps. Only applications with simple payback periods shorter than 15 years are included in this figure.

Buildings with Central Boilers and Chillers

In this section, we discuss options for replacing central boilers and chillers with large heat pumps. While we discussed some system options for general readers above, here we go into greater depth for those interested in a more technical discussion. We did not perform a numerical analysis on conversion economics and energy and emissions savings as the data available are insufficient to provide a foundation for such an analysis. In addition, the economics and energy impacts with these large pieces of equipment are even more site-specific than for the systems discussed above.

CONTEXT

According to the 2012 CBECS, 28% of commercial building floor area is heated with boilers; 21% of commercial building floor area with cooling is cooled using central chillers. Because central chillers are used only in large buildings, this suggests that about 21% of commercial building floor area uses large boilers and chillers, while perhaps 7% of floor area uses smaller boilers combined with smaller types of air conditioners. If we exclude buildings already using electricity for space heating, boilers account for 39% of commercial building floor area that is heated with fossil fuels (EIA 2016b).

In addition, 7% of commercial building floor area is heated with district heating systems, but because most of these systems use fossil fuels, 13% of building floor area heated with fossil fuels is served by district systems. Such systems are used in some central cities and in quite a few universities and hospital complexes. These district systems provide buildings with steam or hot water that serves the same function as steam or hot water provided by boilers. Heat pumps can serve some of these hot water needs, depending on the temperature of the water needed. For buildings with steam heat, a new heating distribution system will generally need to be converted to heat pumps.

For the approximately 21% of commercial building floor area using both large boilers and chillers, plus some of the floor area heated with district systems, a variety of equipment options are available when making the switch to heat pumps. These options include:

- VRF systems
- distributed water-source heat pumps
- modular, packaged, and multi-pipe heat pumps
- ground-source heat pumps (distributed and centralized)

Electric resistance heat options are also available, but these tend to have high operating costs and are not viable in most applications as the primary source of heat unless heat demand is very low (e.g., southern Florida). They can be a backup to some of the options in the preceding list.

For all of these systems, most of the applications to date have been in new construction, and there is limited practical experience with retrofits. In addition, the choice of the best system will depend on many building-specific considerations. For these reasons, we are not able to do an analysis similar to the analyses on RTUs, furnaces, and individual space heaters as discussed in the previous sections. Instead, in the following sections, we provide a qualitative description of opportunities to electrify using each of these five options. We conclude this section with a recommendation for a possible next step for analyzing these options in a sample of actual buildings.

VRF SYSTEMS

We discussed VRF systems, their configurations, and their advantages and disadvantages above. The ability to retrofit a VRF system in an existing building will depend on a variety of building-specific considerations, such as building layout and availability of space for outdoor and indoor units. However, because only small-diameter refrigerant pipes need to be run to rooms, retrofitting a VRF system to an existing building is often easier than for some of the other system types we discuss below. In addition, because VRF systems do not provide fresh air to zones, provisions need to be made to supply fresh air, perhaps using existing systems or perhaps using a new duct system, but typically one with a lower volume than a system sized to move air for space conditioning.[24]

VRF systems have been applied to existing buildings in many instances. Olson (2015) discusses several examples of VRF retrofits in federal buildings managed by the U.S. General Services Administration (GSA). These include the Aspinall Federal Building and U.S. Courthouse in Grand Junction, Colorado, and the Rogers Federal Building in Denver. The Aspinall building is on the National Register of Historic Places. It received a zero-energy-building retrofit that combined extensive energy efficiency measures to reduce load, a combination of a VRF and ground-source heat pumps to provide heating and cooling, and

[24] For smaller applications, this typically takes the form of energy-recovery or heat-recovery ventilators (ERVs or HRVs); for larger applications, this typically takes the form of DOASs.

some photovoltaic panels. The building is in the high desert, and for half the year it has a large temperature differential between the east and west facades. As the sun heats the east side of the building, it requires cooling, while the west side calls for heat. VRF allows the movement of heat from one side of the building to the other. The Rogers building also requires moving heat at different points during the day from one side of the building to the other. VRF was used to save space, both for a boiler and ducts. Due to the retrofits, energy use was reduced 72% in the Aspinall Building and 49% in the Rogers Building (K. Hydras, Office of Federal High-Performance Buildings, U.S. General Services Administration, pers. comm., May 19, 2020).

WATER-SOURCE HEAT PUMPS

We discussed the basics of water-loop systems above. Because of their advantages, water-loop systems are becoming more common in large new buildings. Industry observers indicate that this trend is particularly strong in places such as New York City and California, which are establishing limits on GHG emissions for buildings or limiting use of fossil fuels in buildings.

Water-loop retrofits are still in their infancy. The suitability of a water-loop system depends on the layout of the existing buildings. Retrofitting a water loop requires that new terminal devices be installed. This is a significant renovation, and thus water-loop retrofits might be best when an existing building undergoes a major renovation.

We sought to find examples of water-loop retrofits, but they are very limited. One expert recalled a K–12 school that was retrofit about a decade ago. They reused the hot-water piping as the water loop, added water-source heat pumps to the spaces, and added a closed-circuit cooling tower. The expert could not recall further information, such as where the project was located.

We also heard about one potential project in New York City, but it is not yet public.

Short of a full water-loop retrofit, a variety of commercial buildings have been retrofitted with heat pumps that recover waste heat. For example, St. Michael's Hospital in Toronto recovers heat from the facility's air-handling system and from several water-cooled chillers and uses this heat to warm incoming ventilation air. The system replaced two aging chillers, cost $1.4 million (Canadian), and saves $2,500–6,000 per day depending on the outdoor temperature (Johnson Controls 2008). The Vancity office building in Vancouver recovers heat from its data center to heat the building as long as the outdoor temperature is 5°C or warmer (at colder temperatures, supplemental heat is needed). The system reduced building natural gas use by 96%, GHG emissions by 76%, and water use by 20%. The simple payback for the $222,000 (Canadian) project was 6.3 years before utility incentives and 4.4 years after utility incentives are factored in (Vancouver undated a). In another Vancouver-area project, the Coquitlam Centre Mall recovers heat off its chiller to heat water. The system reduced gas use by 65%, electricity by 5%, and GHGs by 35% at a cost of $110,000 (Canadian). The simple payback was 4.3 years without utility incentives and 2.1 years including the utility incentives (Vancouver undated b).

MODULAR AND PACKAGED AIR-TO-WATER HEAT PUMPS

Modular chillers and heat pumps are small units that can be grouped together to form large units, or "banks." For example, Artic Chill has modules from 15- to 80-ton cooling capacity, and units can be grouped together into banks as large as 800 tons (Arctic Chiller Group 2018). Multi Stack is another major manufacturer.

Packaged chillers and heat pumps are systems with all the needed components combined in a single package. A single building will commonly use several packaged chillers. They range in cooling capacity from just a few tons to over 200 tons. Thus, they overlap with modular systems but typically are larger than modular systems. Manufacturers include Aermec, Carrier, and General Air Products.

Both system types are illustrated in figure 45. Both come in heat pump as well as cooling-only configurations. Both come in air-cooled and water-cooled configurations and can be designed with either scroll or screw compressors.

Figure 45. Modular chiller units on the left, packaged chiller unit on the right. *Sources*: Arctic Chiller Group 2018 and Aermec 2020.

A significant advantage of modular units is that the modules can be small enough to fit into an elevator or other tight spaces, which can aid retrofit projects. However, because each module has its own compressor(s), the compressors are small and not as efficient as larger compressors. On the other hand, modular units can be controlled to stage modules, so only as many modules operate as are needed to serve the load, allowing each module to operate at or near its full capacity, where efficiencies are generally higher. Modular chillers also offer redundancy and flexibility benefits—when one module fails, the others still operate, and it is generally not difficult to add modules if more capacity is needed (Demma 2019). On the other hand, modular units tend to have a higher cost per ton of capacity compared with packaged units (C. Jelen, Application Engineer, Trane, pers. comm., March 25, 2020).

Packaged units can be more efficient than modular units but must often be moved with a crane. Packaged units typically offer larger compressor sizes (lower total number of compressors), which typically leads to a lower cost/ton. Larger compressors can also provide higher full-load efficiencies compared with smaller compressors on modular units. The disadvantage of packaged units is potential capacity turndown and size (typical installation requires a crane).

Both modular and packaged units have been used in building retrofits. For example, the City of Vancouver in Canada has a goal to have zero GHG emissions from its own facilities by 2040. It is now undertaking a multiphase retrofit of city hall. In the first phase, Vancouver rebuilt a wing of city hall and, instead of replacing the existing chiller and boiler system, installed a packaged chiller/heat pump system that provides heating, cooling, and hot water. It also has a gas boiler to provide additional heat in the middle of winter. In the second phase of the project, the city plans to retrofit other portions of the complex to allow use of lower-temperature water for heating, thereby allowing the heat pump system to serve more of the overall building heating load. The city estimates the heat pump system costs 26% more than a like-for-like replacement of the existing system. It further estimates that the heat pump system will reduce natural gas use by 45%, increase electricity use by 8%, and reduce GHG emissions by 34% (the local power grid is mostly hydroelectric power). The city estimates a 6.9-year simple payback period on its heat pump investment (Vancouver undated c).

Another example of a packaged heat pump retrofit is the Denver Water operations complex. The facility needed upgrading, and as part of Denver Water's environmental commitment, it targeted both LEED and net-zero-energy certification. The specific retrofit involved one heat pump that raises the temperature of the inlet city water, which is then piped to four more heat pumps that are optimized to operate at low temperatures (down to –4°F). These latter heat pumps use a gas-injection compressor that allows the heat pump to produce hotter water than a standard heat pump (up to 149°F) (Aermec 2020).

MULTI-PIPE HEAT PUMPS

Multi-pipe systems are heat pumps able to satisfy cooling and heating demands simultaneously. Most commonly, they are four-pipe air-source heat pump systems with two lines for heating (supply and return) and two lines for cooling (also supply and return). A four-pipe unit has three main heat exchangers: a condenser that heats the water for space heating, an evaporator that cools the water for space cooling, and a balancing air coil. The balancing coil works either as a condenser in a cooling mode or as an evaporator in a heating mode to balance the difference between the heating and cooling demands (Trane 2018). A typical multi-pipe system is shown in figure 46. Six-pipe water-source heat pump systems are also available; they include extra "pipes" to connect to groundwater or ground-source boreholes.

Figure 46. Multi-pipe heat pump. *Source:* Trane 2018.

Multi-pipe systems are becoming more common in Europe, where natural gas prices are higher than in the United States and therefore heat pump economics are better. In addition, Europe, as a whole, has taken more steps than the United States to reduce GHG emissions, which encourages use of electric heat pumps. The leading manufacturers are Daikin Applied and Trane. Both companies are exploring opportunities to start selling units in the United States. Current systems on the market range in cooling capacities from about 15 to 800 tons.

Multi-pipe systems can work well where there are substantial winter cooling loads and similarly substantial heating loads in summer. To work well, the heating and cooling demands need to be reasonably balanced. Common applications that often meet these criteria are shopping malls, hotels, and hospitals. The heat pumps typically produce moderate-temperature water (approximately 120°F) and thus can work well in new construction where terminal units can be designed for these temperatures. For higher temperatures, several heat pumps can be employed in a cascading system that raises temperatures in several stages. With such systems, water temperatures as high as 160–180°F can be obtained. Many existing buildings are designed for using hot water in this range. Another challenge with multi-pipe systems is that they are complex and can be more difficult to commission than conventional systems.

Multi-pipe systems have mostly been used in new construction. We heard of one proposed existing building project in France, but it is not yet public. One challenge for existing buildings is the availability of enough area to fit the system on an existing roof. This can be a problem in large cities where roof area is limited. (This same issue can affect water-source heat pumps). For systems connected to a geo-field, space must be available for such a field.

GROUND-SOURCE HEAT PUMPS

Ground-source heat pumps use a ground loop to reject heat during the cooling season and absorb some heat during the heating season. They can be connected to VRF and other distributed heat pumps or to centralized heat pumps, including modular, packaged, and multi-pipe systems.

An example of a distributed ground-source heat pump system is the Aspinall Building described in the section on VRF heat pumps.

An example of a much larger ground-source retrofit project is at Stanford University in Palo Alto, California. Stanford previously used a 50-MW gas-fired cogeneration system to provide heat and power for the campus. In 2015, the university retired this system and replaced it with a series of heat-recovery chillers (essentially heat pumps) that recover waste heat from the campus district chilled-water system, from a ground loop, and from a lake on campus. Throughout the year, the system can satisfy extensive heating and hot water needs. Several large water-storage tanks help to balance loads and preheat or precool water during off-peak hours. On cold days, some supplemental heat is needed, supplied by natural gas–fired hot-water generators. Annually, the heat-recovery system supplies about 90% of heating needs and the natural gas system about 10%. The system serves about 300 buildings and had a capital cost of $485 million. Relative to the system it replaced, the new system is expected to save $420 million over 35 years (Stagner 2016; EPRI 2018).

Some medium-size building examples are also available, including the Muscatine, Iowa, Courthouse complex (Amoroso 2013) and the Cedarville, Arizona, high school, middle school, and elementary school (Open EI 2011).

A ROLE FOR STORAGE

Similar to the Vancouver and Stanford projects in the use of heat-recovery chillers, a few large commercial retrofit projects in New York City are evaluating using heat-recovery chillers and a latent thermal storage device (i.e., ice storage) to be the source of energy for both heating and cooling. In most large NYC buildings, a large amount of "waste" energy is rejected to the atmosphere when economizers cycle ("free cooling") in the winter, while fossil fuels are used to heat the perimeter zones earlier that same day. This waste energy (excess heat in building) can be captured by melting ice in the storage device to cool the spaces (melting ice is storing energy in the form of water). The following morning, the heat-recovery chiller makes ice and "pumps" the energy up to a usable temperature to heat the building. In summer, the storage-source heat pump (SSHP) system can use storage and the chiller to cool the building in the traditional way. By eliminating the free cooling, this energy is recycled and used the following day, displacing the need for fossil fuels as well as eliminating the water use normally evaporated in the free-cooling process. Much-needed storage is added to the building, which adds flexibility to the building's load profile, allowing it to respond to the availability of renewable power sources and better manage peak demand charges (MacCracken 2020). Even with the low cost of fossil fuels recently, heating with the SSHP can be less expensive than a traditional boiler because the SSHP's efficiency is much higher. With the major cost savings from reduced summer electric demands, along with recent incentives from the local utility, paybacks for several proposed New York City projects are in the four- to six-year range (M. MacCracken, President, Calmac Corp., pers. comm., August 20, 2020).

POSSIBLE NEXT ANALYSIS STEP

The previous sections make the case that some commercial buildings can be retrofitted with heat pumps. However, each system type has a variety of constraints, so some applications will make sense and some will not. Available retrofit data are too limited to be able to estimate what proportion of buildings with central boilers and chillers can be converted to heat pumps and which system types might predominate. To answer these questions, a sizable sample of representative existing commercial buildings will need to be examined by engineers, the best retrofit options will need to be identified for each building, and the economics will need to be penciled out. Such a study could include estimates of the need for fossil fuel backup in each of the buildings studied. We estimate that approximately 100 different buildings might need to be examined. This would be a large undertaking and would require a substantial budget. The U.S. Department of Energy would be a logical candidate to undertake such a study. The Electric Power Research Institute might be another option. Such a study should also consider how much of a building's heating load might be served by the optimal heat pump system (many of the preceding examples include some type of backup) and the prevalence of roof or other constraints.

Summary Across Our Three Analyses

Each of our three analyses examines different buildings—those now using RTUs, furnaces, boilers, and space heaters. We combined the results of our three analyses into a single dataset and report the results for median payback by region (figure 47), building type (figure 48), and current HVAC energy-use intensity (figure 49). Consistent with the earlier analyses, median simple payback periods are shortest in the south (West and East South Central, South Atlantic, and Mountain (Hot)) followed by Pacific and Middle Atlantic regions. Median simple payback periods are shortest for inpatient healthcare, malls and other retail, food service, and offices. Payback periods are longest for buildings with low energy intensity for HVAC (less than 12 kBtu/square foot) and about the same for buildings with medium and high intensity.

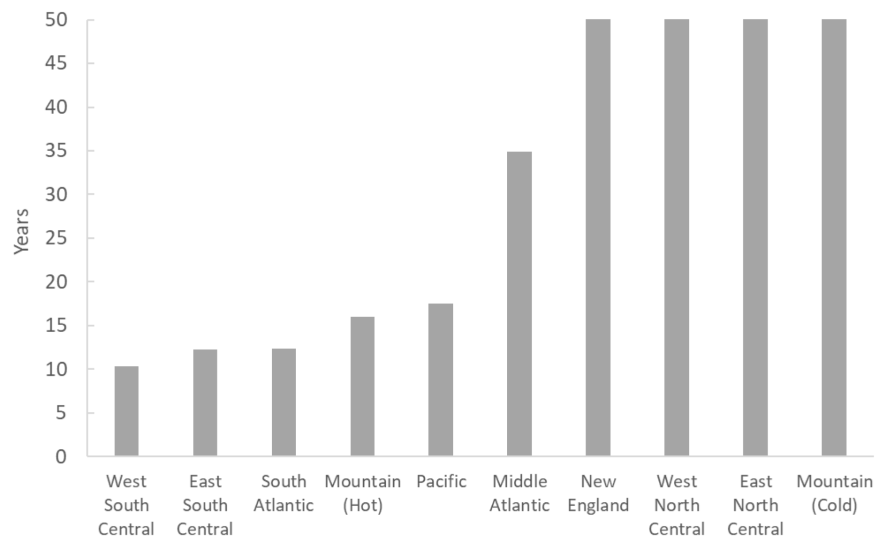

Figure 47. Median simple payback period by region across our three analyses. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

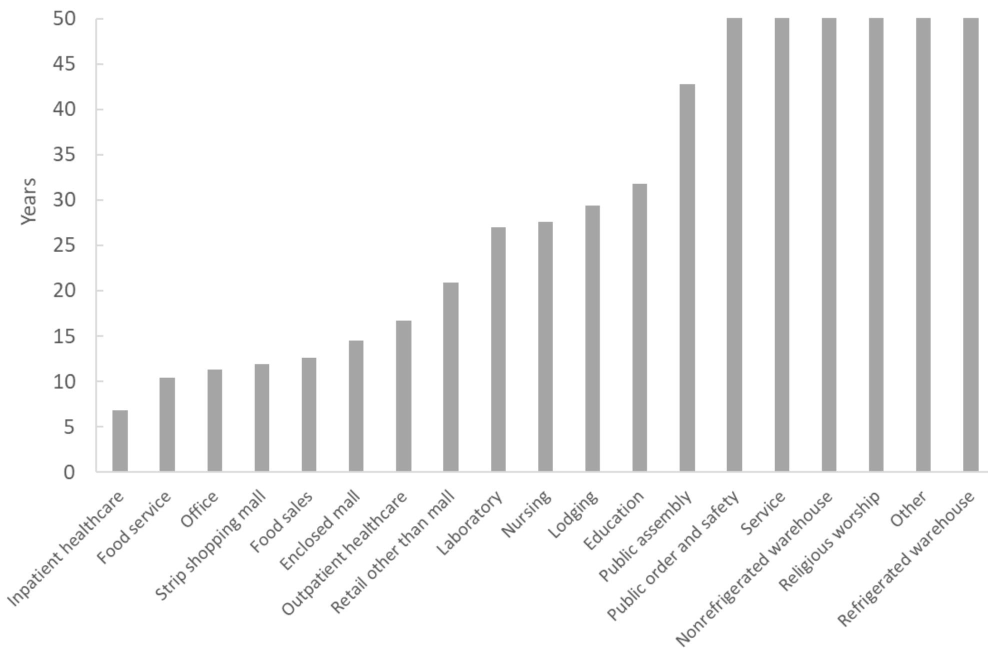

Figure 48. Median simple payback period by building type across our three analyses. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

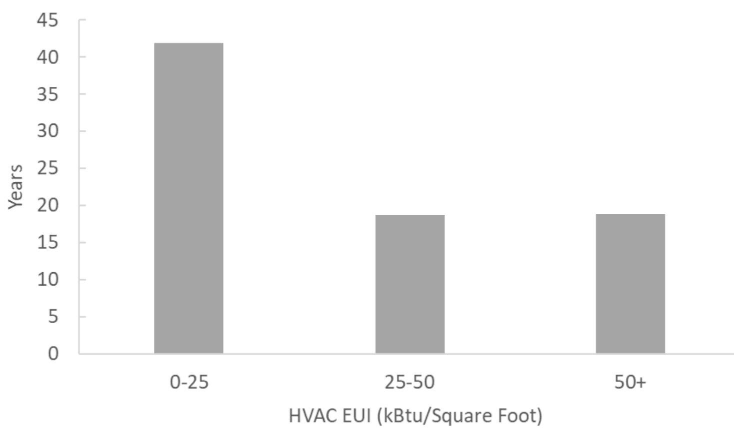

Figure 49. Median simple payback period by current HVAC energy-use intensity (EUI) across our three analyses. This figure does not include the impact of incentives, additional efficiency improvements, or carbon pricing.

We also prepared a combined analysis showing the distribution of simple payback periods under our medium-cost scenario and under the same cost scenario but also including the combined impact of a 20% reduction in building loads due to additional efficiency improvements, a conversion incentive of $100 per ton of cooling capacity, and a carbon price of $50 per ton of carbon dioxide (figure 50). On the left of this figure is our medium-cost case, showing that about 27% of covered commercial building floor area can be converted to heat pumps with a simple payback period of 10 years or less at the time of equipment replacement without any financial incentives. On the right is a similar analysis that also includes the efficiency improvements, incentive, and carbon price. With these program and policy interventions, the portion of floor area with a 10-year payback or less increases to 60%; these programs and policies can more than double the proportion of floor area with potentially attractive economics.

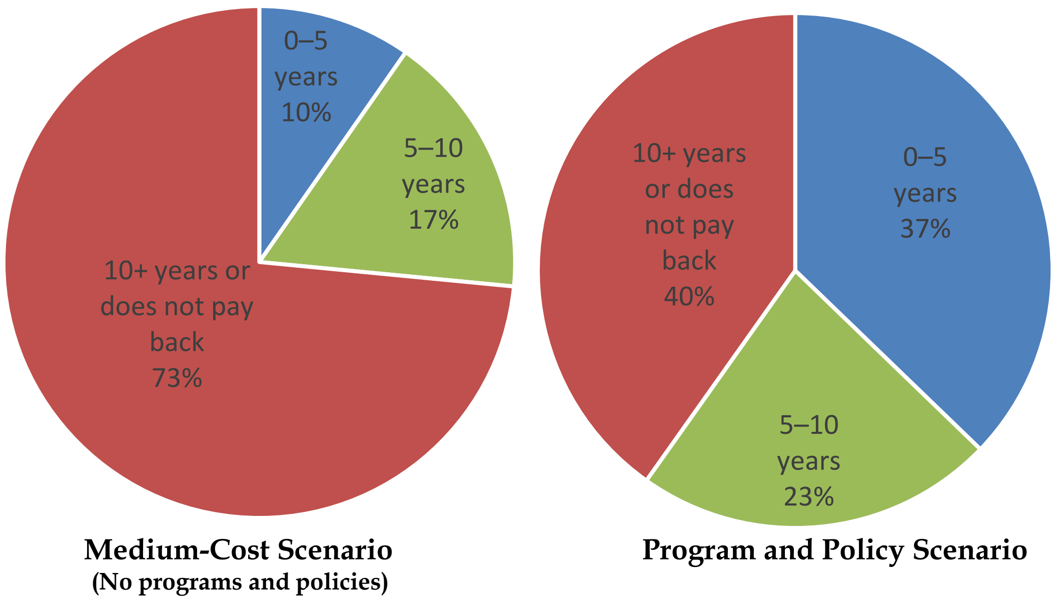

Figure 50. Distribution of the simple payback period by floor area for converting gas-fired rooftop systems, furnaces, space heaters, and small boilers to heat pumps when existing equipment needs to be replaced

Discussion

Our analyses find substantial potential for energy savings and GHG emissions reductions from electrification of commercial building space heating. Across our three analyses (RTUs, furnaces, and boilers/space heaters), available site energy savings total 640 trillion Btu of energy and 36 million metric tonnes of carbon dioxide reductions. These savings are without regard to economics. These savings are 18% and 21%, respectively, of projected commercial-sector site energy use and energy-related emissions for the buildings covered by our three analyses. [25] If we limit the GHG savings to just applications with payback periods of 15 years or less, the GHG emissions reductions total 10 MMT, which is 6% of commercial-sector energy-related emissions for the buildings covered by our three analyses.

While substantial energy savings and emissions reductions opportunities are available, the economics of conversions are challenging absent improved system efficiencies, reduced system costs, financial incentives, and/or a price on carbon emissions. Our analysis on RTUs finds that about 17% of commercial floor area using packaged systems can be electrified with a simple payback period of 5 years or less, and about 29% can be electrified

[25] The emissions reduction figures include emissions in power generation. The energy-use savings are derived from CBECS site energy use (EIA 2016b). Energy-use and emissions data used to calculate the percentage reductions are for 2030 and are from EIA's 2020 *Annual Energy Outlook* (EIA 2020a).

with a simple payback period of 10 years or less. For furnaces, the economics are similar, with 13% having 5-year paybacks and 27% having 10-year paybacks. However, for boilers and space heaters, only about 1% of floor area has a simple payback of 5 years or less and 7% for 10 years or less. Overall, across the three analyses, 10% of floor area covered by these analyses has a simple payback of 5 years or less and an additional 17% of floor area has a simple payback of 5.1–10 years.

The applications with better paybacks are a good place to start. These include much of the southern United States, the "hot" Mountain region, and the Pacific region, where space-heating needs are modest. Applications with better paybacks also include certain building types with long operating hours, such as healthcare, malls and retail, food service, lodging, grocery stores, and offices. However, these are just tendencies; the economics of conversion will vary from site to site depending on energy use, costs, and other factors.

Homes now using oil and propane have better electrification economics than buildings using natural gas. We did not have sufficient data to do a similar analysis for commercial buildings; CBECS does not compile propane consumption data and contains only a limited number of buildings with oil heat.

We did not look at new construction, but on the basis of the work by Billimoria et al. (2018), which found that new homes are often a good electrification opportunity, new commercial buildings are likely to be a good initial opportunity. In new construction, going all electric can avoid the costs of providing gas service to a building and within the building.

Another large opportunity is converting central boiler/chiller systems. Some conversions have been completed, typically as part of major building renovations. However, the economics are highly site-specific, and finding adequate exterior space to locate outdoor units can be a challenge in high-rise buildings. As discussed in the Buildings with Central Boilers and Chillers section, more work is needed to examine conversion options and economics with more-detailed studies on a sample of buildings of different types and geographies.

This analysis is based on systems that are currently widely available and used, such as rooftop heat pumps. Some promising opportunities are on the horizon that could improve conversion economics, such as using VRFs and high-efficiency DOASs to replace RTUs and using modular, packaged, and multi-pipe chiller/heat pump systems to replace large boilers. More work is needed to apply these new approaches to additional buildings and to study these projects to identify and refine best practices.

Given these realities, electrification of commercial space heating is likely to proceed very slowly without policy support. While electrification would reduce GHG emissions and provide other societal benefits, such as improved health (due to reduced emissions of multiple pollutants), there are significant additional costs. Policies and programs can help to realize the societal benefits while improving electrification economics for businesses. Electrification economics can be improved by offering incentives, by placing a price on GHG emissions, and by packaging efficiency improvements with new heat pumps. Our analysis found that when all three are packaged together, 37% of floor area heated with these three system types can be converted to heat pumps with a simple payback period of 5 years or less and an additional 23% with a simple payback of 5–10 years. In addition, in our research on systems to replace boilers and chillers, we learned that in cities with mandatory building performance standards, HVAC companies are finding increased interest from building owners in considering heat pumps when existing heating systems need replacement.[26] Research and development can also be useful in seeking ways to reduce the costs of electrification. Another potentially useful step could be encouraging or even requiring building owners to get a heat pump bid whenever an existing fossil fuel heating system needs to be replaced. Ideally, such bids would be entered in an anonymized database so that good electrification applications can be better identified.

Even with policy support and incentives, electrifying space heating in some types of buildings, such as those with complex HVAC systems or those in cold climates, may still prove challenging. However, with a "don't let the perfect be the enemy of the good" mentality, minor compromises could still result in major carbon and energy savings. For example, the Stanford electrification case study provided in the Ground-Source Heat Pump subsection of the Buildings with Central Boilers and Chillers section shows a project that is able to meet 90% of its heating load through high-efficiency electric technologies, while the remaining 10% is met from backup natural gas boilers during peak heating needs. Attempting to meet the remaining 10% of heating load through electric heat pump technologies can be costly, while including a (sparingly used) natural gas backup boiler can sometimes improve the economics, considering both capital and operating costs. For these economically challenging applications, the inflection point between electric and gas heating is highly site-dependent; while some sites might require 30% of the heating load to be met with fuels, other sites may require only 5%. Some sites, particularly in warm climates, will require no fuel backup (the same may be true for new construction in colder climates where the building can be designed and optimized to use heat pumps).[27] In this analysis, we did not specifically examine the economics of such hybrid systems, but such an analysis would be a useful future step.

The natural gas industry might argue that, instead of electrification, we can decarbonize using gas-fired heat pumps and so-called "renewable gas." However, gas heat pumps are mostly still in development and will likely cost even more than electric heat pumps. As noted earlier, renewable gas supplies are likely limited (NRDC 2020). Hydrogen can be produced in quantity, but hydrogen produced with renewable energy is expensive (e.g., a recent fairly optimistic estimate is a cost of about $6–12 per million Btu wholesale by 2050; Edwardes-Evans 2020), about 1.8–3.6 times the 2030 wholesale natural gas price estimated by EIA (2020a) in the *AEO*. In a decarbonizing world, continued widespread use of conventional natural gas will not be an option; instead, the choice will be between

[26] For more information on building energy performance standards, see Nadel and Hinge 2020.

[27] Using natural gas for backup will make sense only where gas service is available. For areas without gas service, either presently or as the result of possible future retirement of gas distribution systems in some regions, it is less of an option, although propane could be an option for a limited number of hours per year, such as during polar vortex events.

electrification and a gas-based system significantly more expensive than the current conventional system. A future analysis should compare the economics and emissions of electrification versus a system using gas-fired heat pumps and renewable gas.

Finally, we note that electrification of buildings will have profound impacts on utilities and the utility system; these impacts need to be factored into electrification strategies. For example, electric utilities will gain substantial revenues and sales from commercial building electrification. As a result, they should become more active in promoting electrification, perhaps even using some of their own money. In addition, as more buildings are electrified, winter peak demand will grow, which could reduce total system costs in regions that currently have a surplus of winter capacity but could raise system costs in areas that are winter peaking or might become winter peaking in the future. In these latter areas, as buildings are electrified, energy efficiency and demand response strategies will be particularly important (Hopkins, Takahashi, and Nadel 2020).

Study on Heat Pump Retrofits in London, England

Recently, a large study was completed on opportunities to use heat pumps for building space and water heating in London, England (Carbon Trust 2020). The study concluded the following:

- Heat pumps are the primary technology choice for decarbonizing heat in existing London buildings.
- Heat pump technology is varied, versatile, and able to work in all London building types.
- Heat pumps are not a like-for-like replacement for gas boilers or conventional electric heating, and good-practice system design is essential. Good-practice design includes reducing the required flow temperatures, reducing the overall demand for heating, reducing up-front costs for heat pump equipment, and better enabling the building to store heat and benefit from payments for flexible time of use.
- Improved energy efficiency in buildings is a prerequisite for heat pump retrofit at scale and will require significant investment.
- Flexibility of heat demand is essential for a net-zero-carbon energy system, and it can bring significant financial rewards at the individual building level.
- On the basis of current gas and electricity prices, heat pumps will reduce fuel bills compared with conventional electric heating but could increase fuel bills compared with gas unless paired with energy efficiency, best-practice system design, and flexible use of heat.
- The up-front cost of heat pumps is higher than that of traditional alternatives, and many building types will require additional up-front financial support. However, the lifetime financial case for heat pump retrofit is already strong in some building types, such as electrically heated buildings, buildings with a high cooling demand, and buildings that already require major renovations. These building types should be prioritized for heat pump retrofit.

These findings are broadly in line with our findings.

FUTURE ANALYSES

In the preceding discussion, as well as earlier in this paper, we make several recommendations for additional analyses of commercial-building electrification that would be useful. For ease of reference, we list them here:

- Analyze new buildings.
- Analyze buildings now heated with oil and propane.
- Perform a detailed analysis on electrification opportunities in a sample of large buildings.
- Analyze additional electrification options such as VRF systems with high-efficiency DOASs and air-to-water heat pumps. Look at hybrid systems that use mostly electricity but include the option to use fuel on very cold days.
- Compare electrification options with a system that uses gas-fired heat pumps and renewable fuels.

Many other analyses could be useful, of course, but those listed above address limitations in our analysis and would be a good place to start.

Conclusion

Substantial opportunities are available to save energy and reduce GHG emissions by electrifying space heating in commercial buildings. Presently, about 40% of commercial building space heating is provided by electricity, and this report provides multiple case studies of buildings that have converted space heating from fossil fuels to electricity. Our analysis identifies applications that are likely to have better-than-average conversion economics (warm regions, healthcare, retail, food service, and office buildings). For about 10% of floor area, electrification when existing equipment needs to be replaced will pay back in 5 years or less; for about 27% of floor area, the simple payback is 10 years or less. For the majority of floor area, simple paybacks are longer. For these applications, policy choices may well be critical, including programs to promote energy efficiency, electrification incentives, putting a price on GHG emissions, mandatory building performance standards, research and development to reduce electrification costs, and encouraging/requiring bids for a heat pump when an existing heating system needs to be replaced.

In addition, for some buildings with challenging economics, electrification may not be an all-or-nothing proposition. Meeting a substantial majority of the heating load with electricity and using a small amount of fuel backup could still result in major carbon and energy savings while remaining cost effective.

We are still early in the process of electrifying commercial building space heating. Initial projects are showing paths forward. This analysis of opportunities and the need for policies will help accelerate our journey on this path.

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Appendix—Methodology and Assumptions

When heating, ventilation, and air-conditioning (HVAC) systems are at the end of their useful lives in a commercial building, owners and staff must decide how to replace them. Often, they choose the same types of systems that use the same fuel; however, they can consider other options that may save energy, money, and carbon emissions. The goal of our study is to understand the energy savings, economics, and emissions impact of choosing to replace fossil fuel–fired space-heating equipment with a high-efficiency heat pump unit instead of with replacement fossil fuel equipment. Our analysis is based on the most recently available data from the U.S. Energy Information Administration's Commercial Building Energy Consumption Survey (CBECS), which contains a national sample survey of the U.S. commercial-building stock (EIA 2016b).[28]

In this study, we calculate energy cost (and energy use and carbon) savings by replacing existing fossil fuel systems with high-efficiency heat pumps. We considered savings from the current old equipment but then reduced these savings to account for the fact that new minimally compliant fossil fuel equipment is usually more efficient than the older equipment being replaced. The high-efficiency heat pumps in our study always saved cooling and ventilation/fan energy costs. However, for heating, they may reduce energy costs, but they may cost more, depending on the climate, building energy use, and local energy prices.[29] Therefore, the type of calculation we use to determine energy cost/use/carbon savings is as follows:

$$\begin{aligned}
&Total\ energy\ cost\ savings\ over\ existing\ fossil\ fuel\ equipment \\
&= High\ efficiency\ heat\ pump\ savings\ (cooling) \\
&- Minimally\ compliant\ 2020\ fossil\ fuel\ equipment\ and\ air\ conditioner\ savings\ (cooling) \\
&+ High\ efficiency\ heat\ pump\ savings\ (ventilation) \\
&- Minimally\ compliant\ 2020\ fossil\ fuel\ equipment\ and\ air\ conditioner\ savings\ (ventilation) \\
&+ High\ efficiency\ heat\ pump\ savings\ or\ costs\ (heating) \\
&- Minimally\ compliant\ 2020\ fossil\ fuel\ equipment\ savings\ or\ costs\ (heating)
\end{aligned}$$

For energy prices, we used site-specific energy costs in 2012 for each building and then adjusted for regional electricity, natural gas, and fuel oil price trends from 2012 to 2030 per EIA's *Annual Energy Outlook* data (EIA 2020a). [30] Table A-1 depicts these prices.

[28] We used the 2012 CBECS published in 2016. The 2018 CBECS is under way but not yet published.

[29] The impact of humidity on HVAC system performance was not considered in this study.

[30] Propane equipment is not included in the analyses because CBECS does not publish propane energy consumption data.

Table A-1. Average 2012 and 2030 commercial building energy price comparison

Fuel	2012 commercial price	Projected 2030 commercial price	Adjustment factor
Electricity	$0.1012 per kWh	$0.1038 per kWh	+2.50%
Natural Gas	$8.10 per thousand cubic feet	$8.56 per thousand cubic feet	+5.37%
Fuel Oil	$4.02 per gallon	$2.80 per gallon	–43.57%

Source: EIA 2020a

Table A-2 shows the average projected 2030 prices by region for electricity, natural gas, and fuel oil.

Table A-2. Average 2030 commercial-building energy price comparison

Region	Average projected 2030 electricity costs ($/kWh)	Average projected 2030 natural gas costs ($/therm)	Average projected 2030 fuel oil costs ($/gallon)
East North Central	0.114	1.067	0.851
East South Central	0.120	1.021	0.569
Middle Atlantic	0.114	1.051	0.804
Mountain (cold)	0.110	1.031	0.654
Mountain (hot)	0.121	1.163	1.341
New England	0.122	1.022	0.955
Pacific	0.117	1.083	0.714
South Atlantic	0.119	1.059	0.825
West North Central	0.113	1.121	0.835
West South Central	0.119	1.058	0.567

Source: Calculated from EIA 2016b and EIA 2020a

For our carbon-pricing scenario, we assumed a $50/ton fee on carbon dioxide emissions, on both natural gas used in gas heating systems and fossil fuels used to generate electricity. We used a nationwide average of natural gas emissions (EIA 2016a) for fossil fuels and 2030 regional projections for electricity emissions from the grid (Table A-3) (*AEO* 2020).

Table A-3. Emissions data

Region	Emissions type	Metric tons of CO_2 per kBtu
All	Natural gas	0.0000585
All	Fuel Oil	0.0000807
East North Central	Electricity	0.0000446
East South Central	Electricity	0.0000405
Middle Atlantic	Electricity	0.0000242
Mountain	Electricity	0.0000345
New England	Electricity	0.0000117
Pacific	Electricity	0.0000126
South Atlantic	Electricity	0.0000345
West North Central	Electricity	0.0000494
West South Central	Electricity	0.0000400

Source: Calculated from EIA 2016c and EIA 2020a

For our energy efficiency sensitivity scenario, we assumed that loads and capital costs are reduced 20% as a result of energy efficiency investments in a building when the system is replaced. For purposes of this analysis, we assumed that the efficiency investments have a five-year simple payback using site-specific energy use and national average energy prices.

We found simple payback to be one of the most effective ways to display data, but it has limitations. We originally intended to use weighted average (i.e., mean) simple paybacks. However, in some scenarios, equipment had "negative savings," essentially meaning that it cost more over time to operate the high-efficiency heat pump than it saved (most often in cold climates). So we decided to use median paybacks instead. We then manually adjusted negative paybacks to represent very large paybacks (e.g., 5,000 years) to ensure that negative paybacks were not artificially counted as "low" paybacks when calculating the median value. These median values are unweighted, as Excel is not set up to calculate weighted medians. However, we believe unweighted medians are still an effective method to display payback data for this analysis.

For the incentive scenario, we assumed $100 per metric ton for the packaged unit and furnace analyses. We used $500/ton for VRF and mini-splits in the boiler and space-heater analysis, modeled after programs such as the Sacramento Municipal Utility District (SMUD) Commercial Electrification Solutions incentives (SMUD 2020).

All final analyses use CBECS weighting factors, which approximate the number of similar buildings for each building type for each climate zone. In addition, weighted factors were multiplied by CBECS "percent heated by" data to ensure that we captured only floor area served by the equipment identified in this study.

PACKAGED UNITS

The CBECS database contains 1,624 sample buildings with fossil fuel packaged equipment, not including vacant buildings.[31] Because CBECS does not indicate the size of the equipment, we made some assumptions about the equipment in the building. For simplicity, we assumed the average rooftop unit (RTU) in the building is 10 tons, which falls between DOE's "small" (7.5-ton) and "large" (15-ton) units (DOE 2015b). The median lifespan of these units was calculated to be 21.67 years after we averaged from the lifespans of small and large units from DOE's *Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Small, Large, and Very Large Commercial Package Air Conditioning and Heating Equipment* (DOE 2015b). We used engineering rules of thumb to estimate the HVAC size as shown in table A-4.

Table A-4. Cooling square feet per ton cooling HVAC ton estimates matched with closest CBECS building type designation.

Building type	Square feet per ton (cooling)
Small/medium office	350
Large office	325
Laboratory	200
Nonrefrigerated warehouse	400
Food sales	300
Public order and safety	300
Outpatient healthcare	200
Refrigerated warehouse	400
Religious worship	225
Public assembly	225
Education	450
Food service	175
Inpatient healthcare	275
Nursing	275
Lodging	375
Strip shopping mall	250
Enclosed mall	250
Retail other than mall	250
Service	200
Other	400

Smaller numbers indicate more space conditioning. *Source*: Bell and Angel 2015.

[31] From this point forward, we use the terms *packaged units* and *RTUs* interchangeably in this section.

Heat pump capacity is also very dependent on temperature, so using manufacturer data averaged from four high-efficiency heat pump manufacturers (Daikin, Lennox, Carrier, and Trane), we developed a capacity curve adjustment, which we correlated to heating degree days (HDDs), as shown in figure A-1 (Oak Ridge National Laboratory 2005).[32] The colder the outdoor temperature, the larger the heat pump must be to meet heating loads. The sizing estimates in table A-4 were multiplied by the adjustment factor in figure A-1 to determine the needed equipment size for each building in our sample.

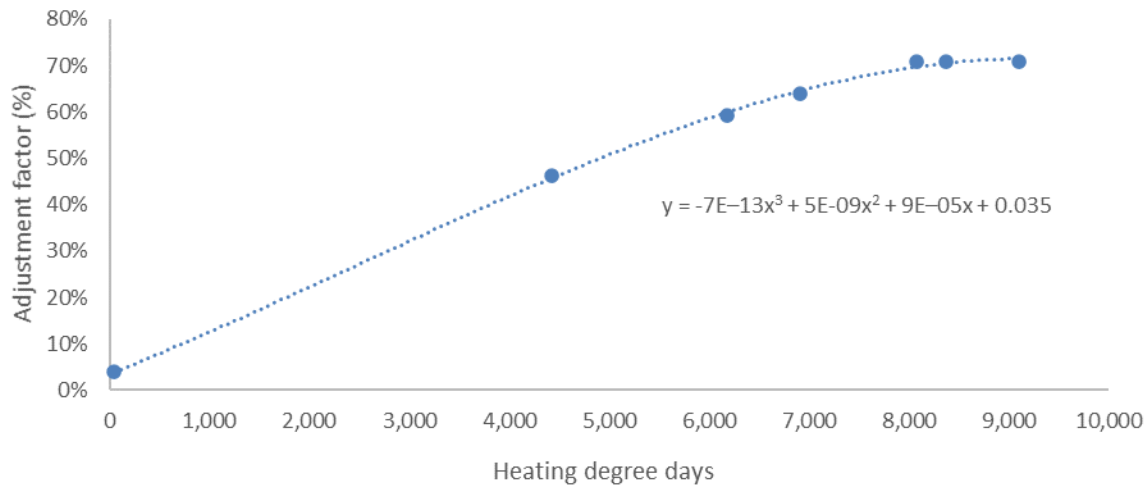

Figure A-1. Capacity adjustment factor based on heating degree days (HDD). HDDs by city obtained from Oak Ridge National Laboratory (2005).

Cooling and heating energy savings (or increases) were calculated on the basis of energy efficiency ratings. This analysis compared a rooftop gas-pack unit meeting the minimum efficiency standards DOE set in 2016 (12.7 IEER[33], 80% thermal efficiency) with a high-efficiency heat pump composite of units offered by four major manufacturers (16.33 IEER, 2.43 COP at 17˚ F). We compared these units with the average gas-pack system that would have been installed 11 years ago (roughly half the average equipment lifespan), which would have had to meet DOE's 1995 standards (this standard only used EER[34] as a metric, but we estimated 9.1 IEER is roughly equivalent to the standard, and the baseline furnace remains 80%). This determined energy savings before adjusting for the higher efficiency of new minimally compliant furnaces and air conditioners.

We incorporated an adjustment factor for cooling based on results published in DOE's RTU Challenge study that correlate slightly higher energy savings for greater cooling degree

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[32] Our adjustment approach is based on single-capacity systems designed to serve the peak load. For variable-capacity systems, sizing can get more complicated, but we did not include these considerations in this analysis.

[33] IEER stands for Integrated Energy Efficiency Ratio, which is an efficiency measurement based on the weighted average of EER ratings at four load capacities – 100%, 75%, 50%, and 25%.

[34] EER stands for Energy Efficiency Ratio and is the efficiency rating of an air conditioner or heat pump based on a test procedure run at the unit's 100% load capacity.

days (CDDs) (Wang and Katipamula 2013). We also incorporated an adjustment factor for heating coefficient of performance (COP) based on average seasonal COP manufacturer data published for 47°F and 17°F and site-specific HDDs to reflect lower heat pump energy savings with more HDDs, as shown in figure A-2.

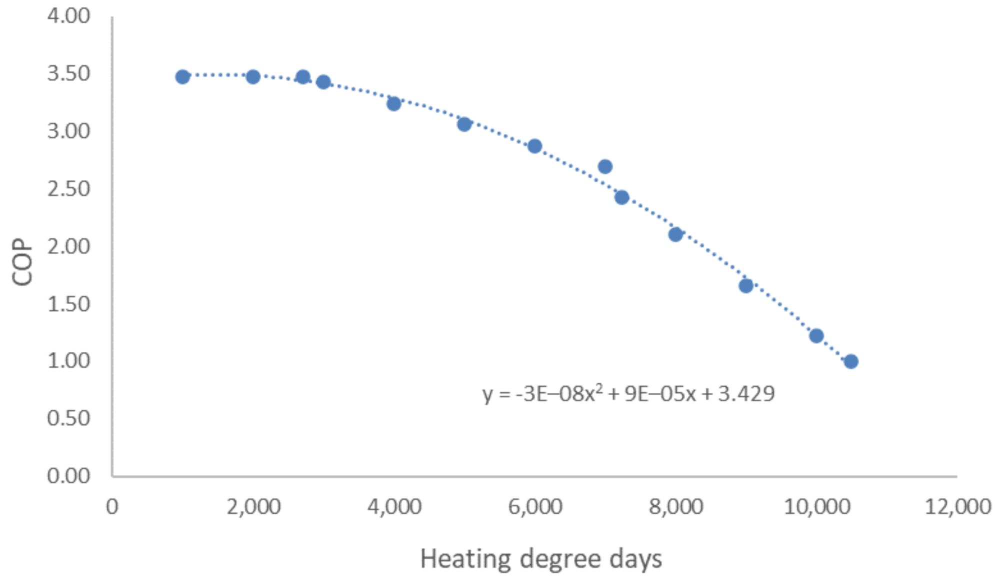

Figure A-2. Estimated coefficient of performance by heating degree days

Fan energy savings were assumed to be 64%, a mix of high-efficiency two-stage and variable-speed heat pump units compared with a single-stage air conditioner. This is the average of a DOE RTU Challenge study, which estimated 69% fan energy savings for variable-speed RTUs over single stage (Wang and Katipamula 2013), and ASHRAE's modeling analysis, which estimated 58% fan energy savings for two-stage units (Lord and Stein 2012).

Incremental costs to upgrade from a natural gas–fired packaged unit to a high-efficiency heat pump packaged unit were estimated to be $292/ton. This is the average between our high cost of $397/ton (RSMeans 2020) and our low cost of $137/ton (SCE 2020). Both estimates include equipment and installation costs.

Table A-5 illustrates the differences among the heating, ventilation, and cooling savings for each climate zone for the packaged unit analysis.

Table A-5. Average cooling, ventilation, and heating savings from installing a rooftop heat pump when an existing packaged system with gas heat needs to be replaced

Region	Average cooling savings ($)	Average ventilation savings ($)	Average heating savings ($)
East North Central	222	1,380	(1,043)
East South Central	437	1,038	63
Middle Atlantic	443	2,479	(936)
Mountain (Cold)	80	1,103	(983)
Mountain (Hot)	484	1,759	(532)
New England	332	2,799	(1,154)
Pacific	411	1,809	(468)
South Atlantic	783	2,324	(453)
West North Central	236	925	(474)
West South Central	992	1,119	32

FURNACES

The CBECS database contains 318 fossil fuel furnaces that are paired with split-system or single packaged air conditioners, with the majority (75%) being split systems. We mostly approached this analysis like the packaged unit analysis above. However, unlike the packaged unit analysis, which was a one-to-one replacement, our furnace analysis is a one-to-two replacement. This analysis compares installing a heat pump system to replace a furnace/air-conditioning system. We assumed that the heat pump would be installed when the air conditioner failed. For the comparison case, where the system is replaced with a minimally compliant air conditioner and furnace, we assumed the furnace would last an additional five years, and we depreciated the cost at a 5% discount rate. In addition, we assumed the units installed in these buildings were closer to residential in size, approximately four to five tons, so some of the data used in this analysis come from residential air conditioner and heat pump standards.

For split systems, we assumed a medium incremental cost increase of installing a high-efficiency split-system heat pump of $467/ton, with a low incremental cost of $330/ton and a high of $660/ton. The medium costs represented costs obtained from Southern California Edison's Heat Pump, Unitary and Air-Cooled HVAC, Commercial – Fuel Substitution workpaper, which obtained costs from several online sources, including www.acwholesalers.com, www.acdirect.com, and www.nationalairwarehouse.com. We obtained labor costs from RSMeans Online. ACEEE found these incremental costs to be comparable to the DOE *Residential Central Air Conditioners and Heat Pumps* and *Commercial Warm Air Furnaces* Technical Support Documents (DOE 2016b, DOE 2015a). Low and high costs represent ±41% of the medium cost, which reflects the high- and low-cost difference for the packaged unit analysis.

For furnaces paired with packaged air conditioner systems, we assumed the same cost difference as for the packaged unit analysis.

For system sizing, we used the same rules of thumb table as in the packaged unit section. We used manufacturer data to create new capacity and COP[35] adjustment curves for cold climate (Carrier, York, Trane, and Rheem) and ENERGY STAR® Most Efficient (Daikin, Carrier, Lennox, and York) (EPA 2020). Note, we considered only fully ducted heat pumps in this analysis and did not consider ductless/ducted mini-splits or variable refrigerant flow (VRF) systems (ductless heat pumps will be considered in the analysis on space heaters).

For calculating energy savings, we divided our high-efficiency split-system heat pumps into two categories: cold-climate heat pumps, which averaged specs from the top four cold-climate heat pumps (20.3 SEER[36] and 11.4 HSPF), and regular high-efficiency heat pumps, which averaged the top four ENERGY STAR Most Efficient Units (20.9 SEER and 10.9 HSPF) (EPA 2020). We used cold-climate heat pumps for buildings in areas with at least 5,000 HDDs and regular high-efficiency heat pumps for areas with fewer than 5,000 HDDs. Packaged air conditioners used the same efficiency requirements as packaged units in the section above. Note that we did not create a cooling adjustment factor for the furnace study due to lack of available data.

We calculated cooling and heating energy savings (or increases) on the basis of energy efficiency ratings. This analysis compared the heat pumps described in the preceding paragraph with air conditioners meeting the minimum efficiency standards DOE set for residential central air conditioners and heat pumps in 2015 (13 SEER for split-system units and 14 SEER for single packaged units), with furnaces meeting a minimum requirement of 80% AFUE. We compared these units with the average air conditioner and furnace system that would have been installed eight years ago (roughly half the average equipment lifespan), which would have had to meet DOE's 2008 standard (13 SEER, 80% AFUE furnace), to a high-efficiency split system (cold climate or regular) or packaged system, with efficiencies as listed above. For heating, our analysis used site-specific HDDs and manufacturer equipment ratings to calculate site-specific heating COP, using an approach very similar to the one described above for RTUs.

Fan energy savings are estimated to be 68% for the high-efficiency split system and packaged high-efficiency heat pump units over the minimally compliant existing and 2020 air conditioners, based on ventilation savings values from DOE's residential air conditioner and heat pump rulemaking technical support document (DOE 2016b).

BOILERS AND SPACE HEATERS

For the final scenario, we examined buildings with boilers and space heaters that could potentially be replaced with ductless mini-split heat pumps[37] or VRF heat pumps. On the basis of available data, we assumed that mini-splits would be installed in small buildings up

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[35] Although these smaller units use HSPF as a heating efficiency rating, manufacturers also use COP data, which we used to create adjustment curves.

[36] SEER stands for Seasonal Energy Efficiency Ratio. It is an energy efficiency rating similar to IEER, but the unit is tested at different temperatures rather than different load capacities.

[37] The term "mini-splits" is used interchangeably with "ductless heat pumps."

to 5,000 square feet[38] and that VRFs could be installed in buildings between 5,001 and 100,000 square feet (GSA 2012). We assumed buildings over 100,000 square feet would be better served by other system types. We considered buildings with existing split-system and packaged cooling systems, with room air conditioners or no cooling. The CBECS database contained 544 buildings of 100,000 square feet or less that use natural gas or fuel oil unit heaters or boilers.

Like the furnace analysis, this study often considers a two-to-one replacement, for example, replacing a boiler and air conditioner with a VRF system. However, we also included buildings without cooling in the analysis, in which case it was a one-to-one replacement, for example, a boiler with a VRF system. Also like the furnace analysis, when considering the minimally compliant fossil fuel replacement scenario when replacing two systems, we assumed that system replacement happens when the more expensive system needs replacement (e.g., the boiler), with the second system (e.g., the air conditioner) normally to be replaced after. To account for this, we assigned either a discounted credit or an additional discounted cost. Because boilers' projected lifespans are nearly 25 years (DOE 2016a), they received a credit for the additional years they lived beyond an average air conditioner system, discounted at 5%. Conversely, space heaters are assigned an additional discounted cost when paired with split-system and packaged air conditioners because unit heaters are projected to last 13 years (ASHRAE 2015); for simplicity, we assumed a 16-year lifespan for all air conditioners on the basis of 15.63 years for residential-size heat pumps (DOE 2016b). Space heaters received a credit when paired with room air conditioners because room air conditioners are expected to last approximately 10 years (DOE 2020).

We assumed the average lifespan of ductless mini-splits is about the same as a ducted residential heat pump, which we previously estimated to be 15.63 years (DOE 2016b). We also found multiple sources that estimated VRF lifespan ranging from 15 to 20 years (GSA 2012; EMS 2015; Bulger 2019). For simplicity in our payback and life-cycle cost assessment calculations, we decided to set mini-split and VRF lifespans at the same number and conservatively assumed a 16-year life expectancy.

Heating equipment installed costs were assumed to be $26.01 per thousand Btu per hour (MBH) for space heaters, using RSMeans data for a 100 MBH gas-fired suspension-mounted unit (RSMeans 2020) and $33.40 per MBH for an 80% thermal efficiency gas-fired boiler (EIA 2018). Because CBECS provides only kBtu heating energy data, we used available data to estimate heating hours by correlating equivalent full-load heating hours in various U.S. cities to their HDDs to produce figure A-3.

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[38] In NEEA's *Very High Efficiency Dedicated Outside Air System Pilot Project Report,* we found evidence that ductless heat pumps could be installed in buildings larger than 5,000 square feet, such as the 5,735 square foot office building project in Libby, Montana. However, we felt that 5,000 square feet was a reasonable cutoff point for this study (NEEA 2020).

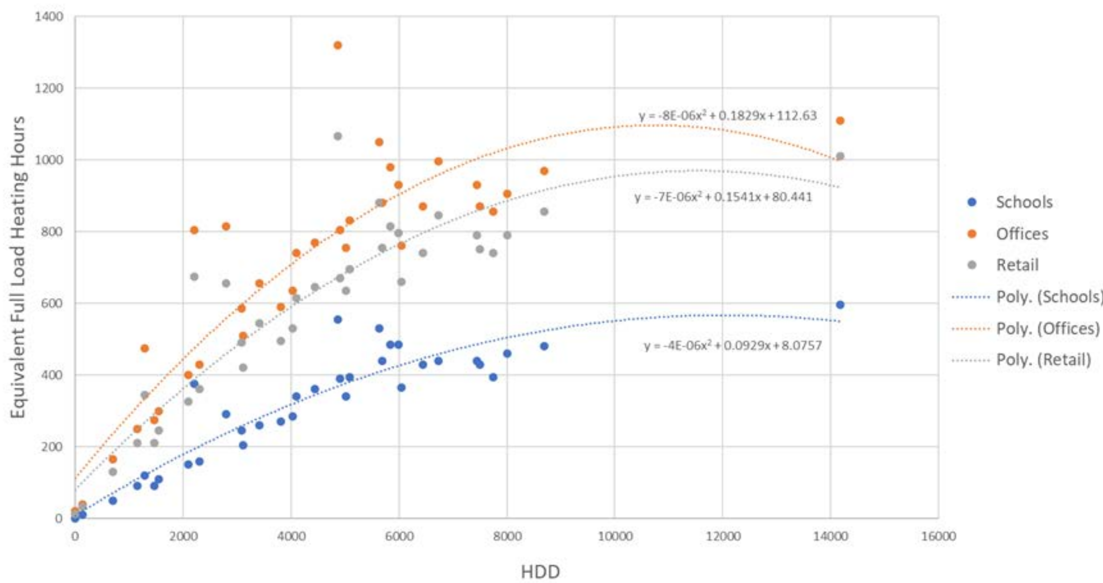

Figure A-3. Equivalent full-load heating hours based on HDDs. Equivalent full-load heating hours data taken from a modified 2000 ASHRAE study that has been updated with the assumption that energy-saving strategies would be used during unoccupied periods (CDH 2000). For building types, we assumed Education would follow the Schools curve; Strip Shopping Mall, Enclosed Mall, Retail Other than Mall, Food Sales, and Food Service would follow the Retail curve; and all other building types would follow the Office curve. HDDs by city obtained from Oak Ridge National Laboratory (2005).

For cooling equipment, split and packaged air conditioner costs remained the same from the furnace analysis, and room air conditioner installed costs were assumed to be $533.84 based on an average cost of units without reverse cycles, with louvers from DOE's 2020 room air conditioner rulemaking preliminary Technical Support Document (DOE 2020).

The medium installed cost for ductless mini-splits was assumed to be $1,730 per cooling ton, based on RSMeans data for 2-ton split ductless systems (RSMeans 2020). The medium installed cost for VRF systems was assumed to be $2,863 per ton, based on the RedCar Analytics (Bulger 2019) study. High and low costs were assumed to be ±41% to remain consistent with the packed air conditioner and furnace analyses. We compared total VRF costs to another study that estimated costs of $18 per square foot, and we found them to be comparable (Strecker, Iplikci, and Cryane 2016).

VRF IEER ratings were determined by averaging top-performing units from four manufacturers in the AHRI Directory database: Mitsubishi, LG Electronics, Samsung, and Daikin (AHRI 2020). Mini-split SEER ratings were determined from four of the top units listed as ENERGY STAR Most Efficient units from Mitsubishi, LG Electronics, Fujitsu, and Daikin (EPA 2020). Because of the setup of our study, for some buildings we had to compare equipment that used different measurements of efficiency. For example, a medium-size building may have been using residential-size split systems that use the SEER metric, while we assumed that building would be best served by VRF, which uses IEER. For this, we assumed that SEER and IEER were roughly equivalent. For buildings with room air conditioners, we assumed that the metric CEER was roughly equivalent to EER (EPA 2014).

To equate it with SEER and IEER, we divided it by 87.5%, which is suggested by LearnMetrics as the Air-Conditioning, Heating, and Refrigeration Institute's recommended conversion (LearnMetrics 2020).

Over the past few years, research has shown that IEER ratings for VRF equipment can be inflated compared with their actual performance in buildings, resulting from limitations with the test procedure (PG&E 2018). Researchers, efficiency advocates, and manufacturers collaborated to develop an improved test procedure during DOE's Appliance Standards and Rulemaking Federal Advisory Committee (ASRAC) negotiations that preliminary estimates show would reduce IEER ratings about 12% (DOE 2019). However, this revised test procedure is not yet in effect. Therefore, we deducted 12% from the projected efficiency of VRF and mini-split systems, as researchers have found similar rating inflations in ductless heat pumps (Stephens 2018).

VRF capacity adjustments are based on published heating capacity reduction charts available from a Mitsubishi VRF design document (Mitsubishi Electric 2012). Because published capacity data for these units are very difficult to find, we used the same adjustments for ductless mini-splits. Like the other analyses, we made capacity adjustments on the basis of low- and high-temperature COP performance data published from top VRF units from four manufacturers, including Mitsubishi, LG, Samsung, and Daikin. Manufacturers of ductless mini-splits did not publish this data, so we assumed the same COP curve as for VRF units.

We also adjusted for distribution losses. On the basis of available data, we noted that boilers lose roughly 10% capacity via distribution through pipes (Thermodyne 2020), and ducted air-conditioning systems lose about 15% on average (Fisk et al. 2000). We were unable to find estimated refrigerant piping losses for VRF systems, so we estimated these to be 5%. Therefore, we estimated that VRF has a 5% reduction in heating losses compared to boilers and 10% in cooling losses compared to air conditioners. We applied these adjustment factors in heating and cooling to show the slight expected increase in performance for VRF and ductless heat pump equipment.

Because of the lack of available fan/ventilation savings, we conservatively used the same values from the packaged air conditioner analysis. For this study, we did not consider the additional costs of installing a dedicated outside air system (DOAS) or heat-/energy-recovery ventilation system because it is unclear whether buildings would be installing them. However, the California Statewide Codes and Standards Enhancement 2022 Title 24 HVAC controls draft report finds that a decoupled DOAS can save VRF energy by allowing it to cycle off when not in use (instead of continuously providing outside air, as is common practice) and by providing ventilation heat recovery in mild climates (Minezaki et al. 2020).The addition of DOASs might help improve the energy savings and economics of VRF in certain climates.

The other components of the analysis were completed similarly to packaged air conditioners and furnace studies.